Joint CTEQ Meeting and POETIC 7 (7th International Conference on Physics Opportunities at an ElecTron-Ion-Collider)
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Nuclear PDFs at an EIC

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1. Introduction.

2. Present status.

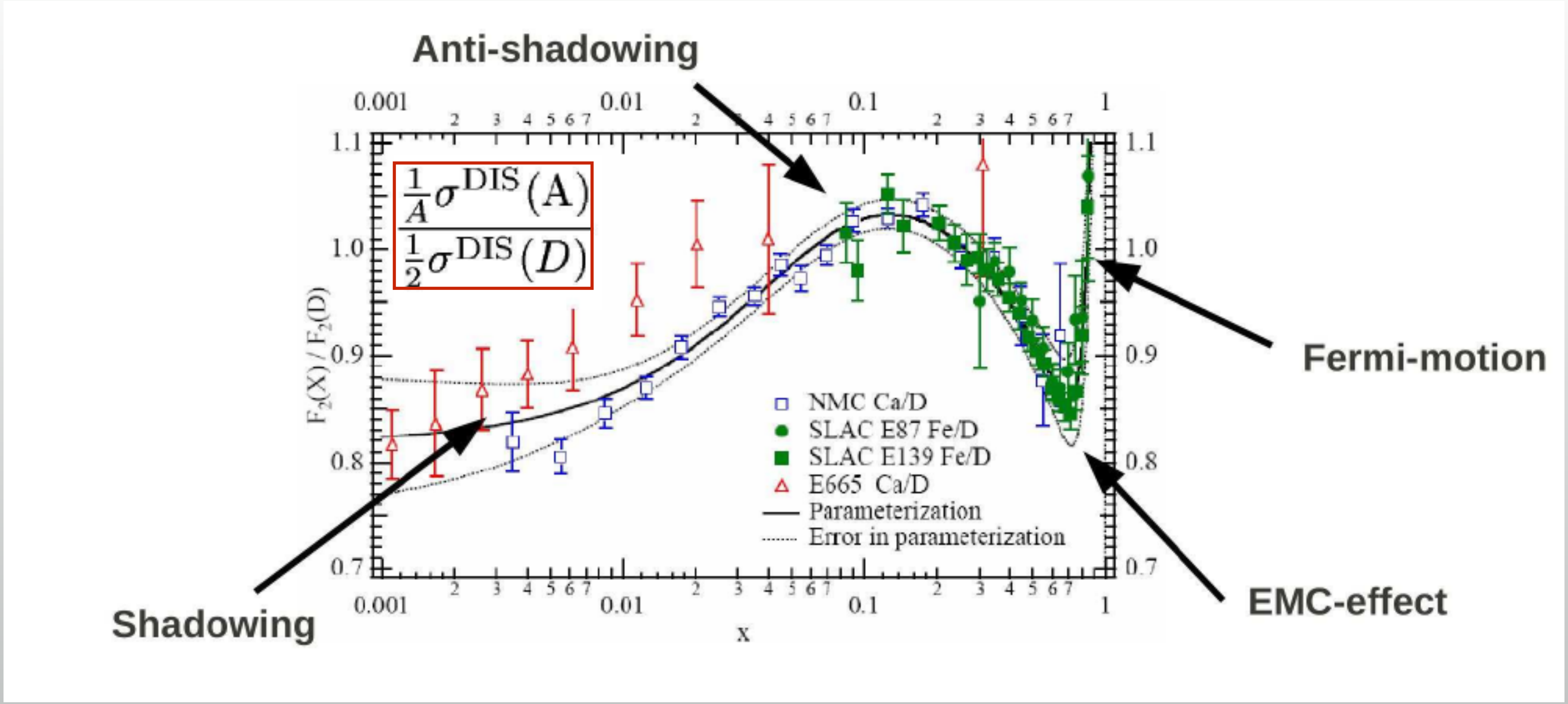
3. Impact of LHC pPb data.

4. Electron-ion colliders:
    ➜ Framework.
    ➜ The EIC.
    ➜ The LHeC/FCC-he.
    ➜ Deuteron.

5. Conclusions.

Note: I focus on the determination of nPDFs from data through DGLAP fits (so Q^2 will be perturbative to apply collinear factorisation), not on the origin of the different effects seen in structure functions or the motivations for physical initial conditions.

Nuclear structure functions:



- Different explanations for the different regions (many of them not based on a partonic picture): <u>not the subject of this talk</u>.

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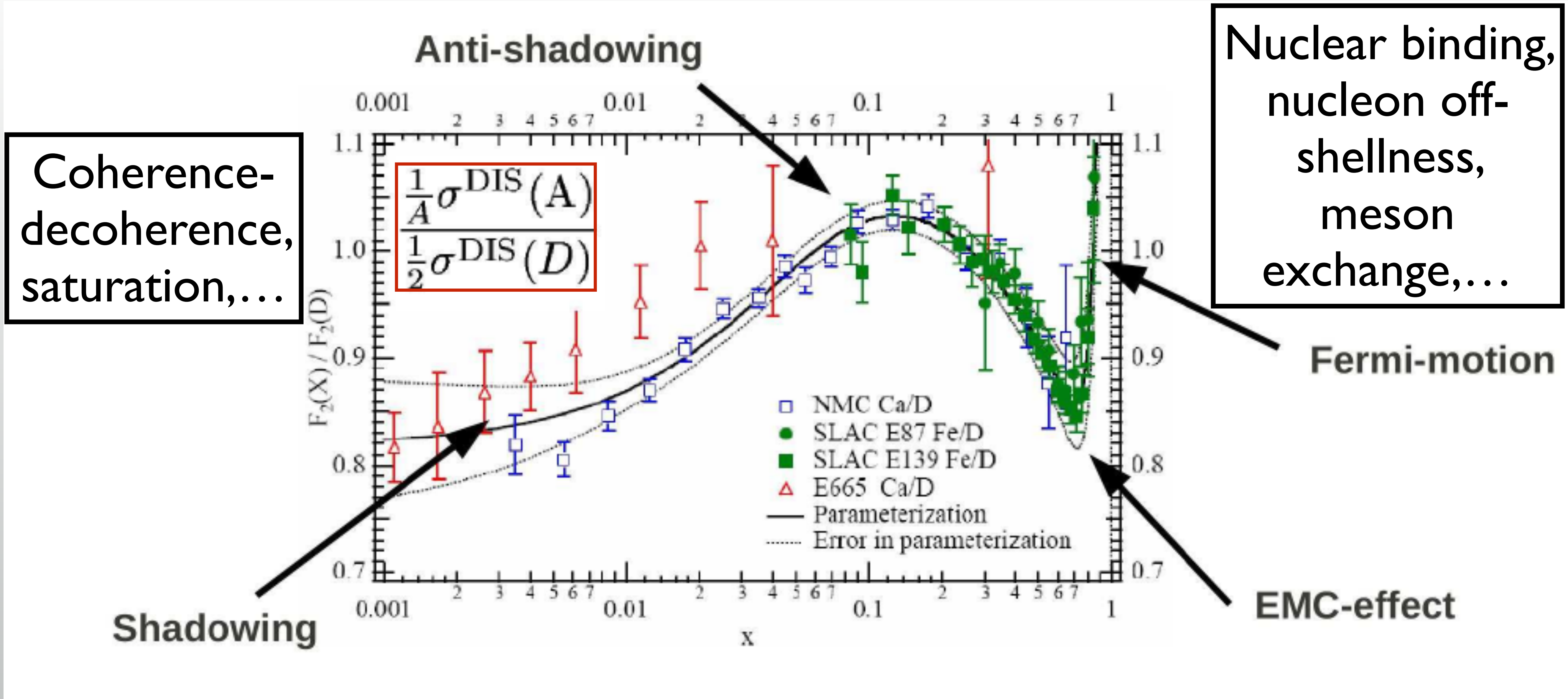

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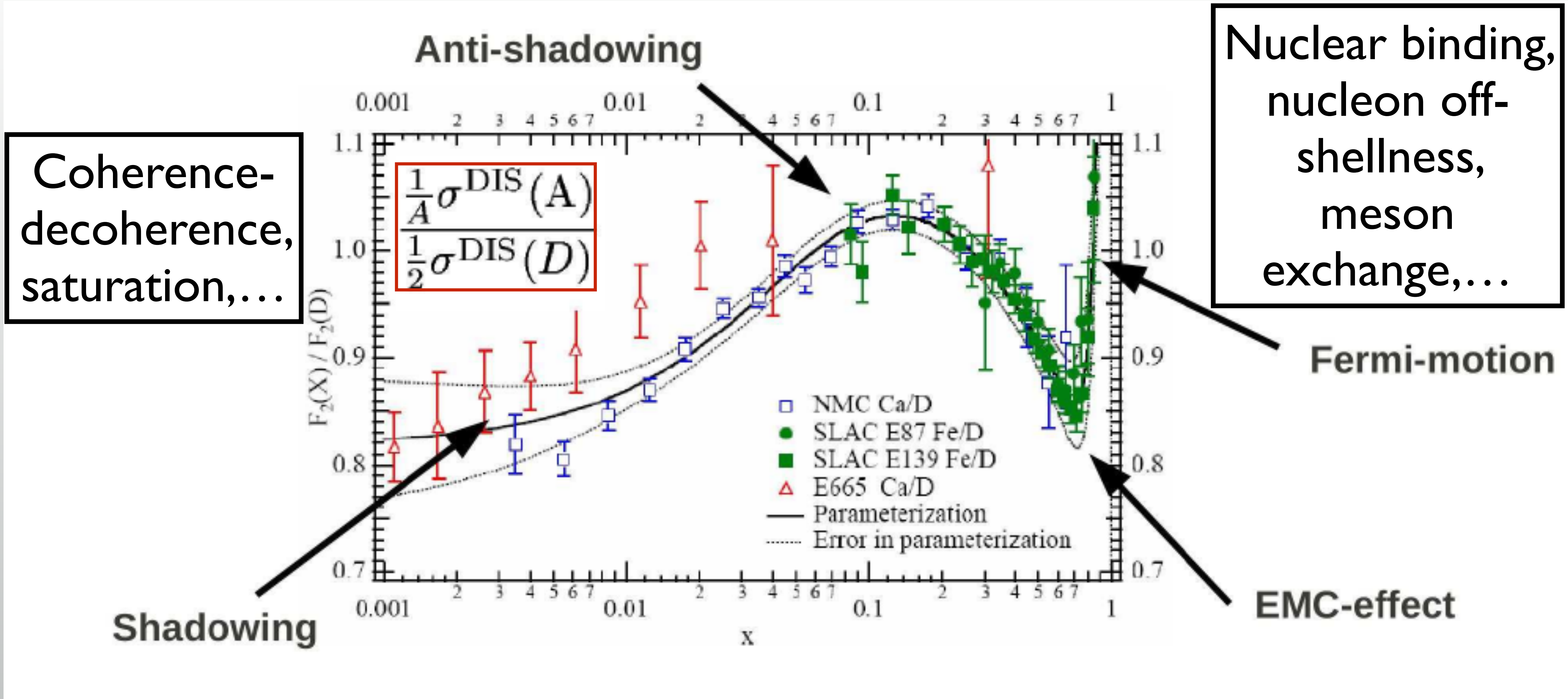


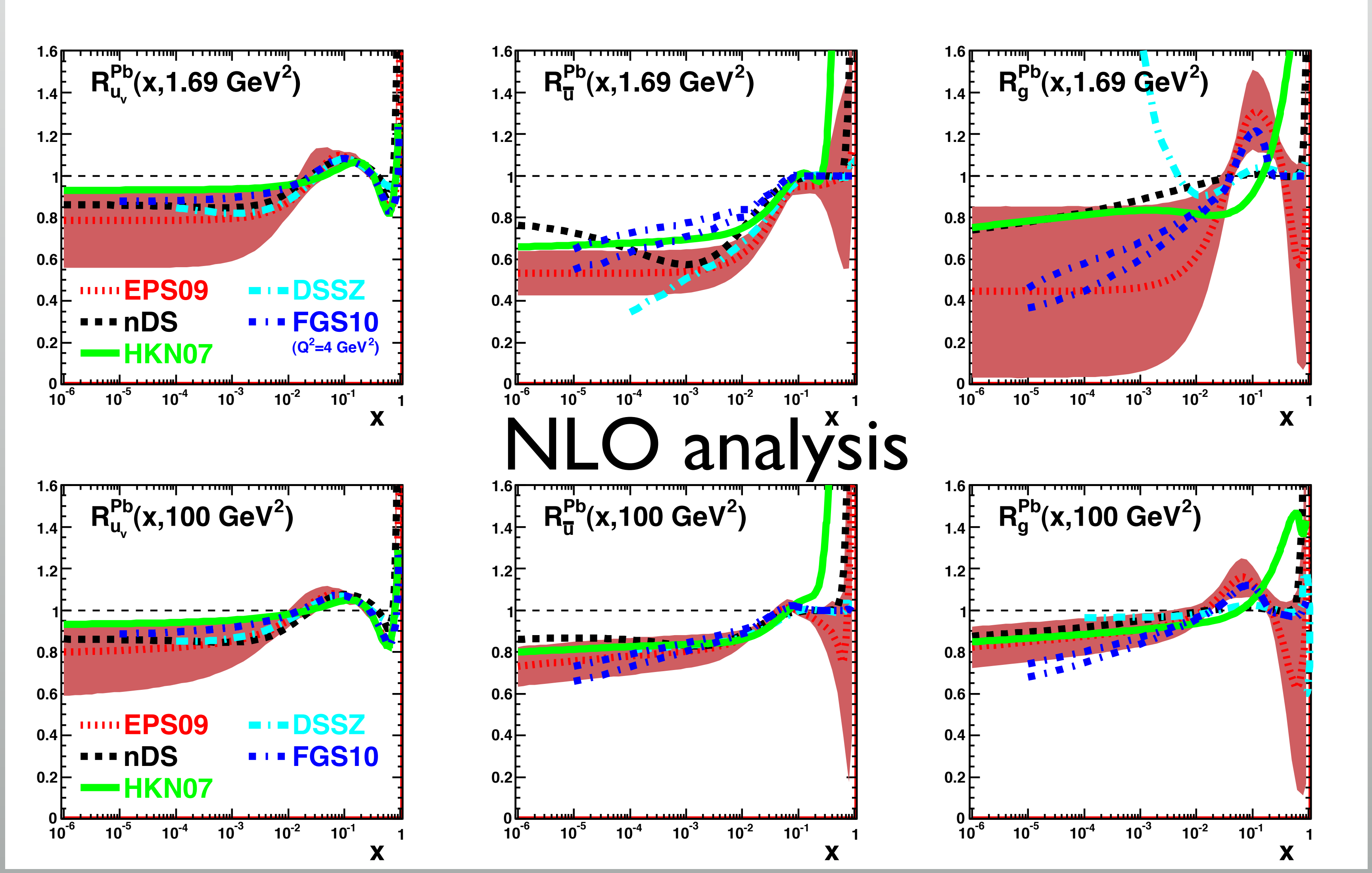
- Bound nucleon $\neq$ free nucleon: search for process independent nPDFs that realise this condition in <u>collinear factorisation</u>.

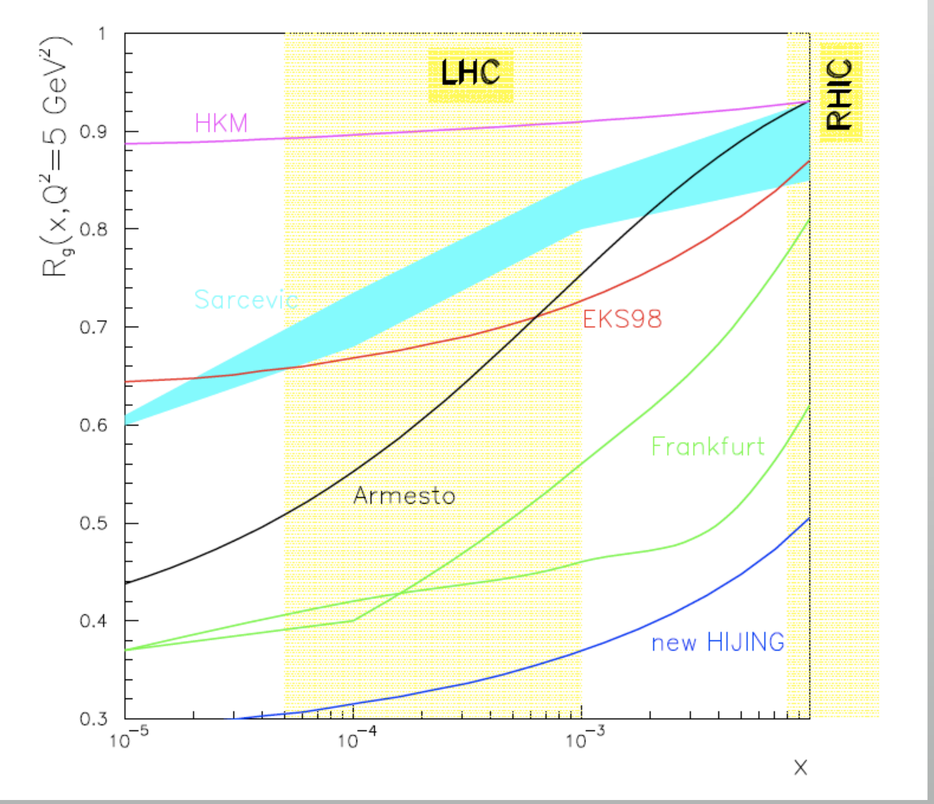
$$\sigma_{\mathrm{DIS}}^{\ell+A\to\ell+X} = \sum_{i=q,\overline{q},g} \underbrace{f_i^A(\mu^2)}_{\text{Nuclear PDFs, obeying the standard DGLAP}} \otimes \underbrace{\hat{\sigma}_{\mathrm{DIS}}^{\ell+i\to\ell+X}(\mu^2)}_{\text{Usual perturbative coefficient functions}}$$

nPDFs:

$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

- Lack of data ⇒ large uncertainties for the nuclear glue at small scales and x: problem for benchmarking in HIC in order to extract 'medium' parameters.





CERN Yellow Report on HP, 2004

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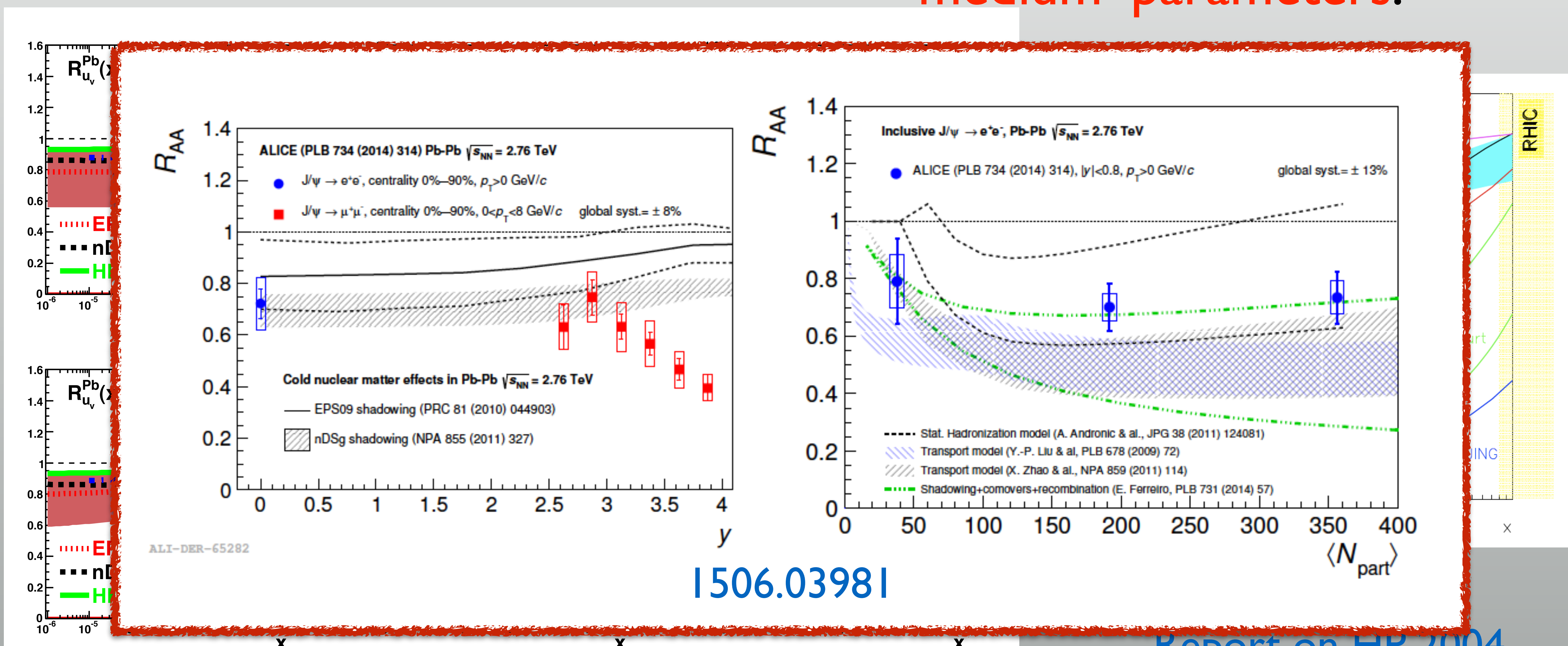

Report on HP, 2004

Procedure of extraction:

PDFs, or nuclear effects on them, parametrised at initial scale $Q_0 \gg \Lambda_{QCD}$ employing sum rules (parametrisation biases)

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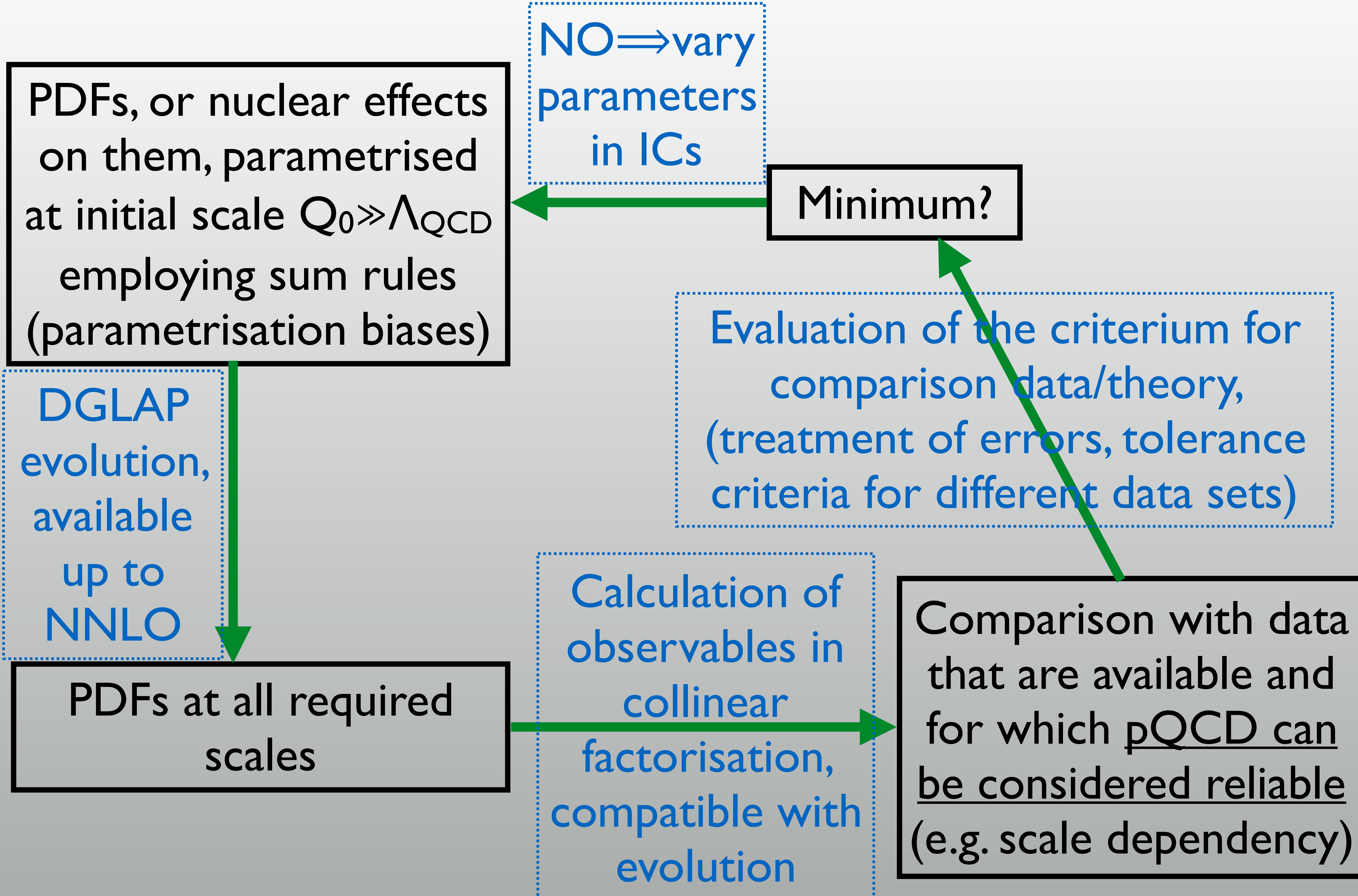
Calculation of observables in collinear factorisation, compatible with evolution

Comparison with data that are available and for which <u>pQCD can be considered reliable</u> (e.g. scale dependency)

Evaluation of the criterium for comparison data/theory, (treatment of errors, tolerance criteria for different data sets)

Minimum?

Procedure of extraction:



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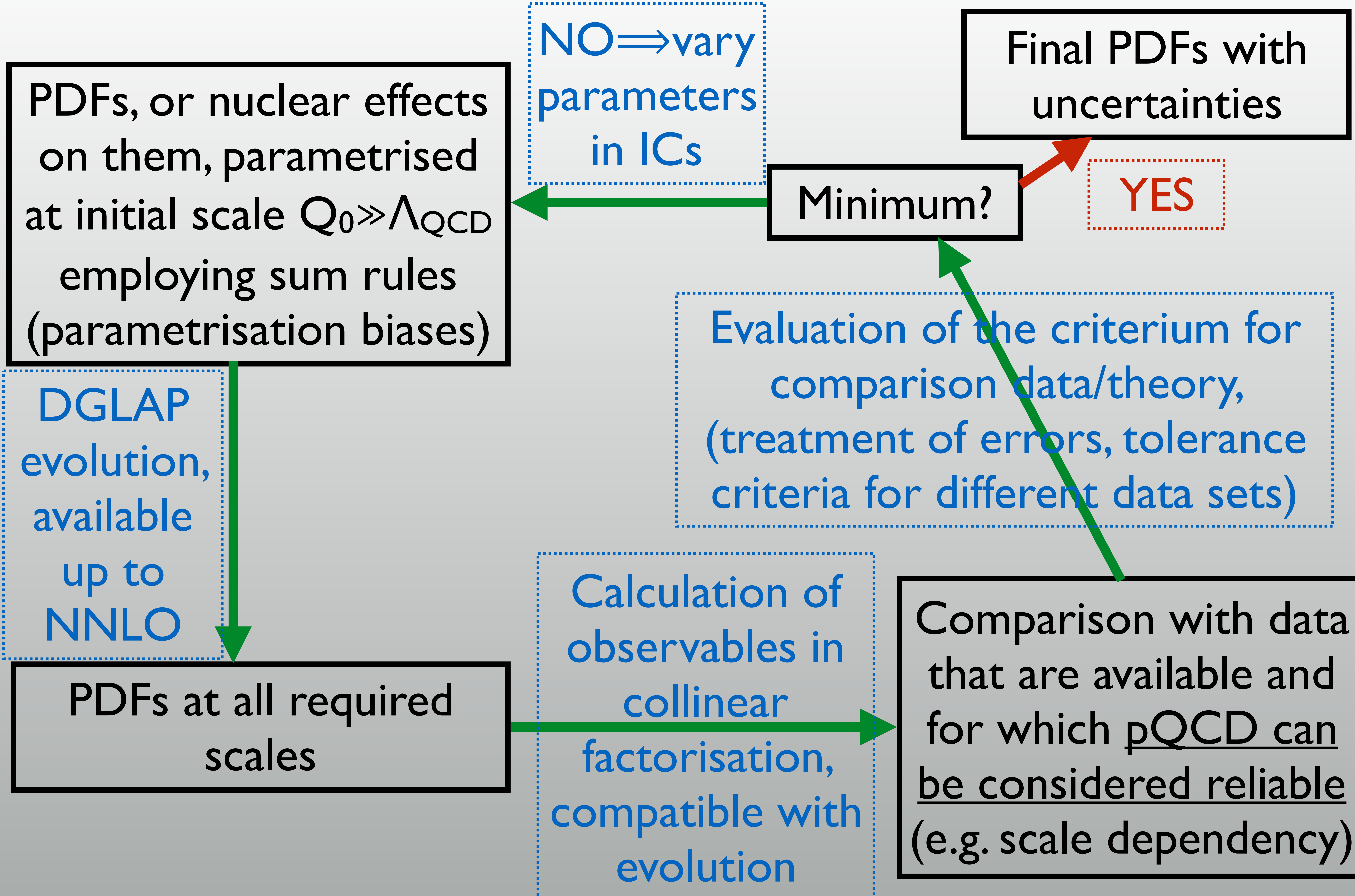

Procedure of extraction:

NO⟹vary parameters in ICs

Final PDFs with uncertainties

PDFs, or nuclear effects on them, parametrised at initial scale $Q_0 \gg \Lambda_{QCD}$ employing sum rules

Minimum?

YES

- One of the most standard procedures in HEP: development of fast (public) tools for evolution and computation of observables.
- Problems known by the proton community.
- Its aim is extracting PDFs from data, assuming that collinear factorisation works.

NNLO

PDFs at all required scales

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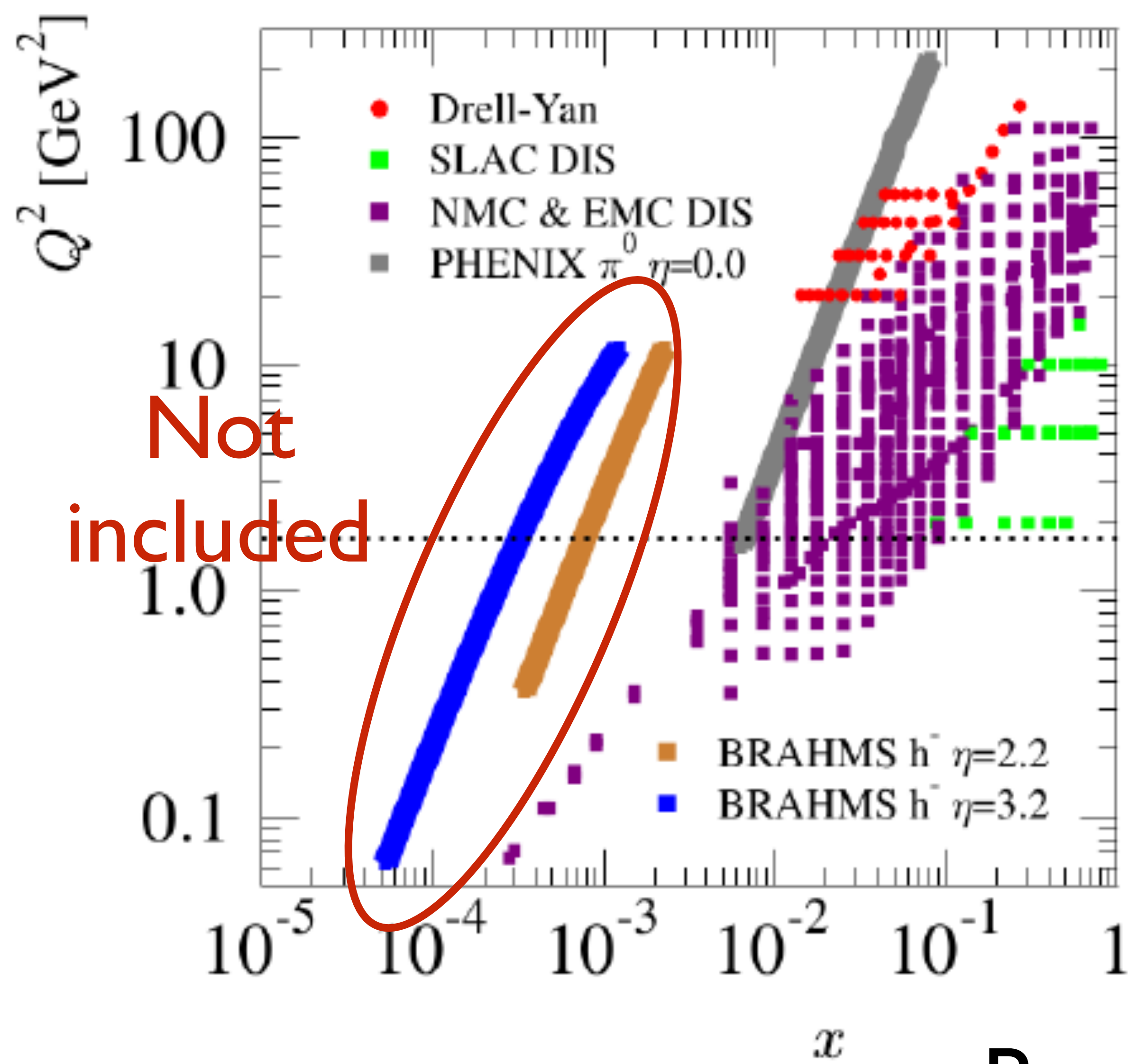
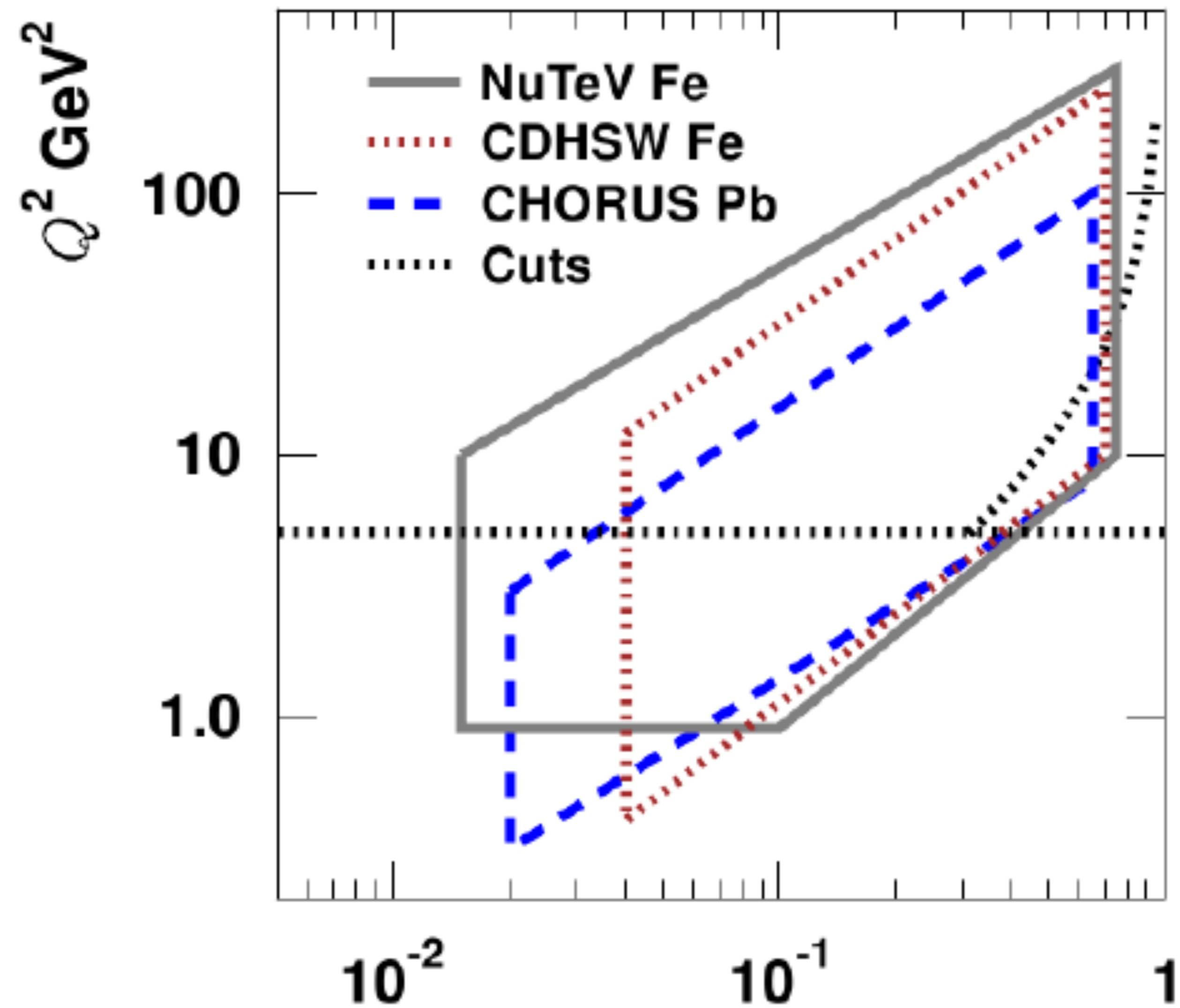
Available sets:





Presently included data

- Not enough data for any single nuclei: A-dependent parameters in either the ratios or the PDFs.
- Valence for $x>10^{-2}$ constrained by DIS, sea for $x>10^{-2}$ by DIS+DY, glue for x~0.1 by DIS Q^2-evolution and RHIC pions.

Available sets:

SET		**HKN07** PRC76 (2007) 065207	**EPS09** JHEP 0904 (2009) 065	**DSSZ** PRD85 (2012) 074028	**nCTEQ15** PRD93 (2016) 085037	**KA15** PRD93 (2016) 014036
data	eDIS	✔	✔	✔	✔	✔
	DY	✔	✔	✔	✔	✔
	π^0	✘	✔	✔	✔	✘
	νDIS	✘	✘	✔	✘	✘
# data		1241	929	1579	740	1479
order		NLO	NLO	NLO	NLO	NNLO
proton PDF		MRST98	CTEQ6.1	MSTW2008	~CTEQ6.1	JR09
mass scheme		ZM-VFNS	ZM-VFNS	GM-VFNS	GM-VFNS	ZM-VFNS
comments		$\Delta\chi^2=13.7$, ratios, no EMC for gluons	$\Delta\chi^2=50$, ratios, huge shadowing-antishadowing	$\Delta\chi^2=30$, ratios, medium-modified FFs for π^0	$\Delta\chi^2=35$, PDFs, flavour sep., not enough sensitivity	PDFs, deuteron data included

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	eDIS	✔	✔	✔	✔	✔
			✔	✔	✔	✔
			✔	✔	✔	✘
			✘	✔	✘	✘
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- Centrality dependence (EPS09s) not from data but from the A-dependence of the parameters.
- Several models provide it: Vogt et al., FGS, Ferreiro et al.,…

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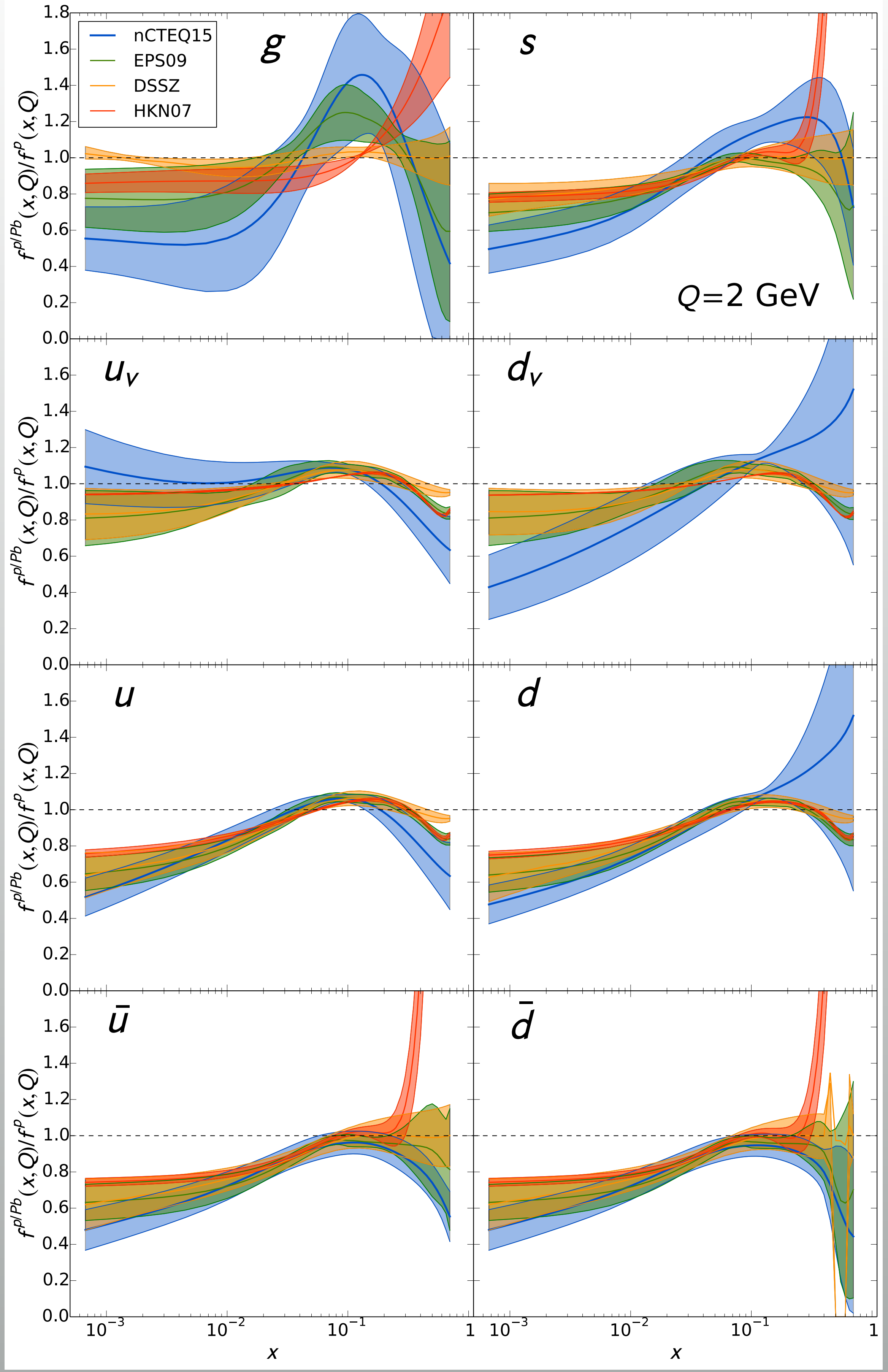

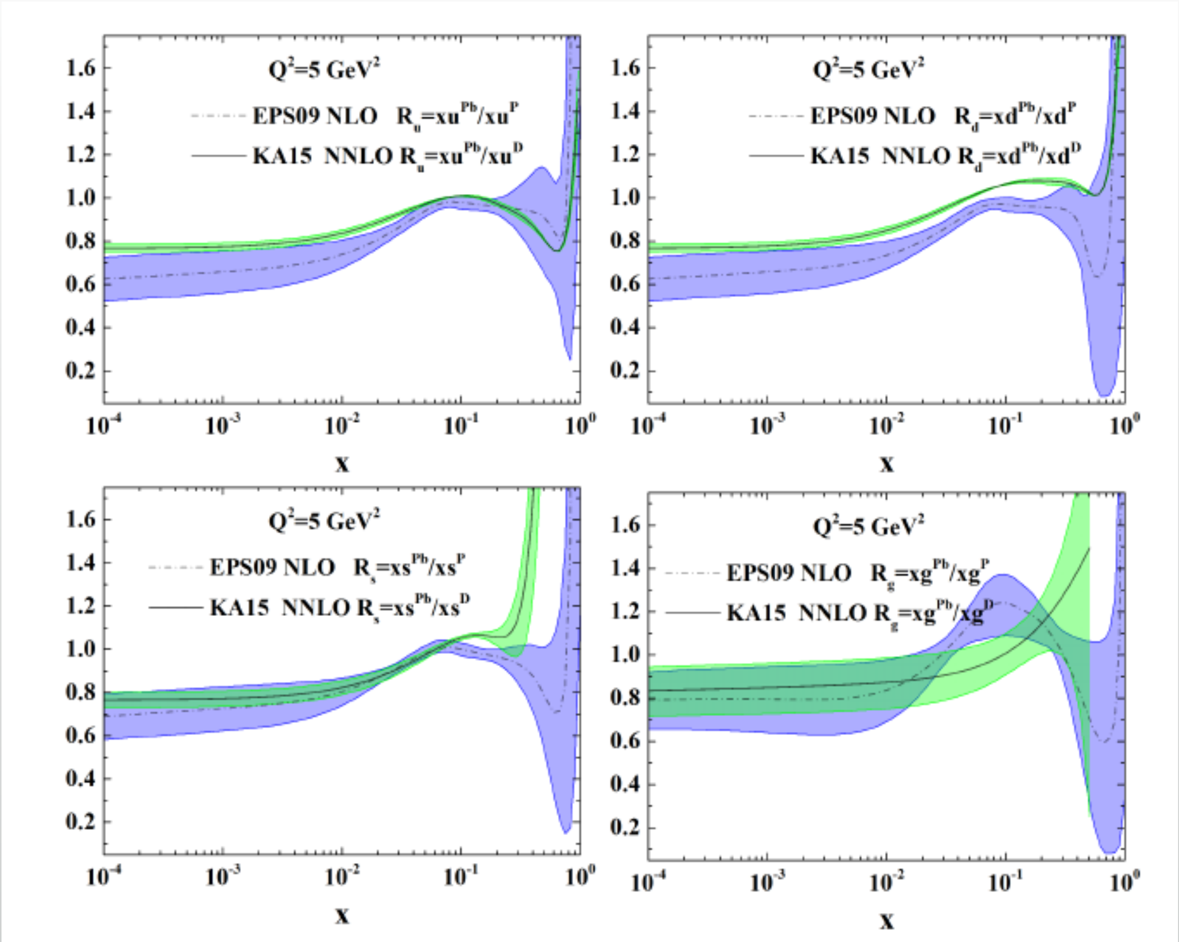

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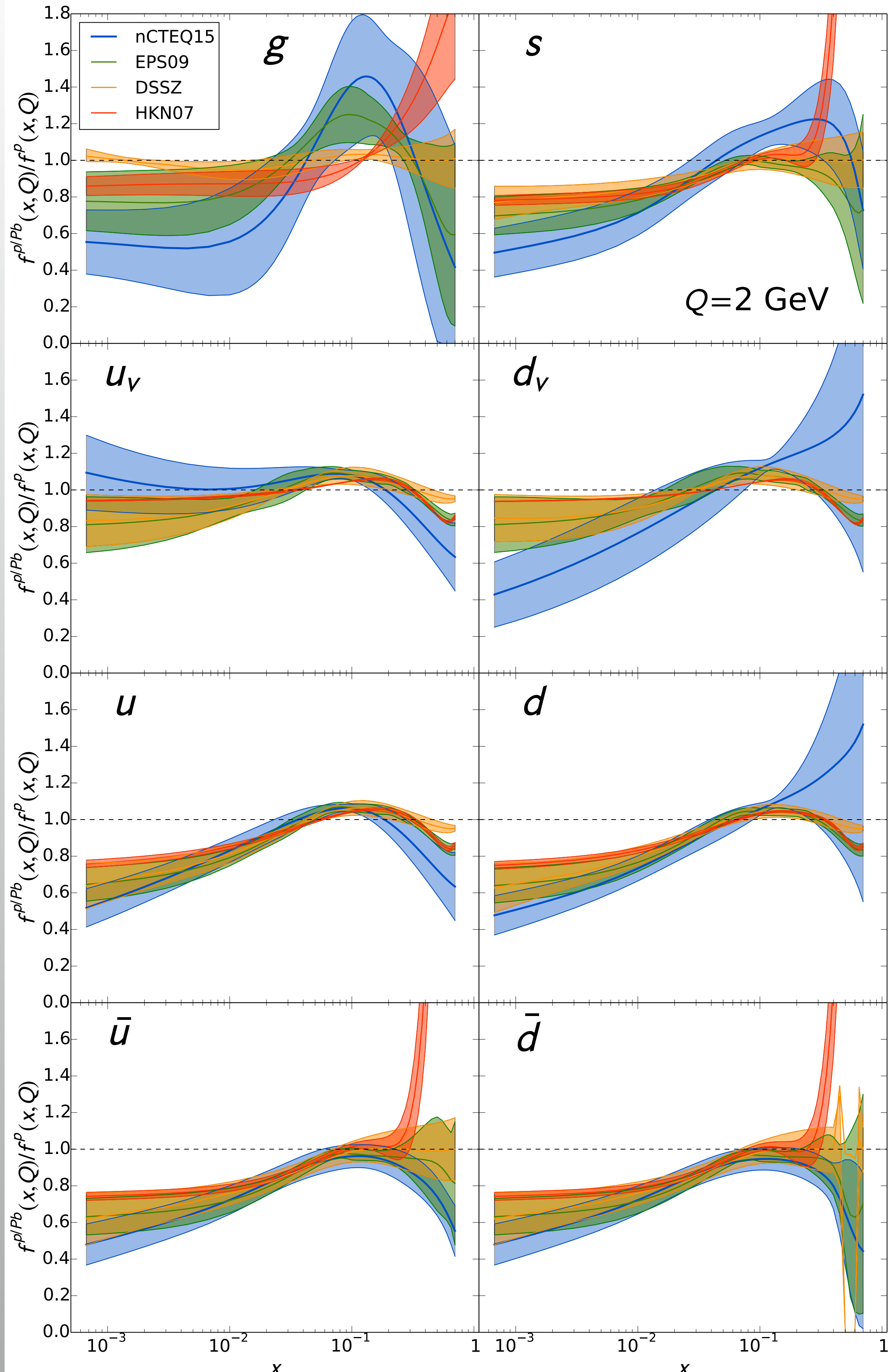

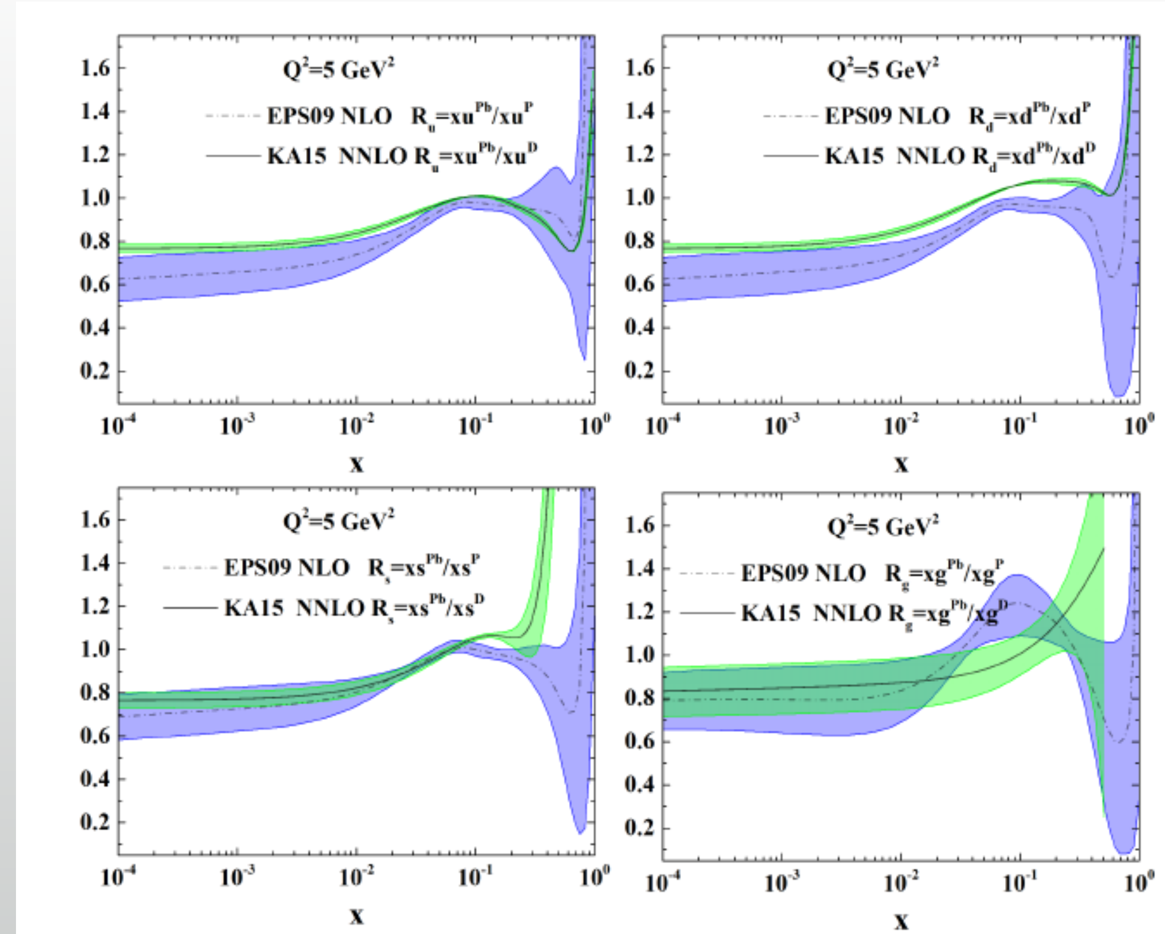

- No constrain at high x (g) and low x (g, valence, sea).
- Data do not require flavour separation (R_u=R_d).
- LHC data next: EPS16, AZ,…
- Initial condition (plus sum rules) drive the extrapolations.

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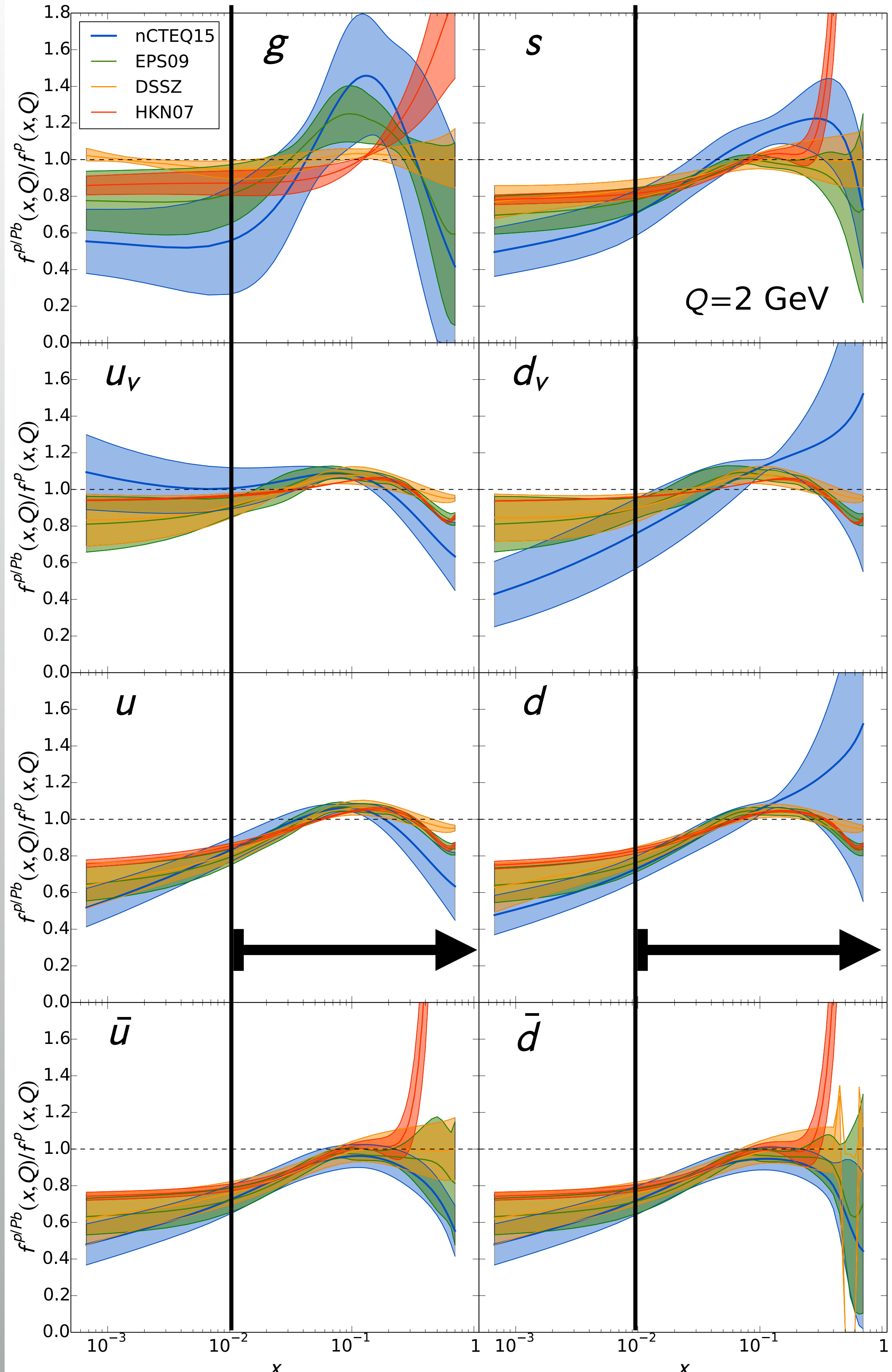

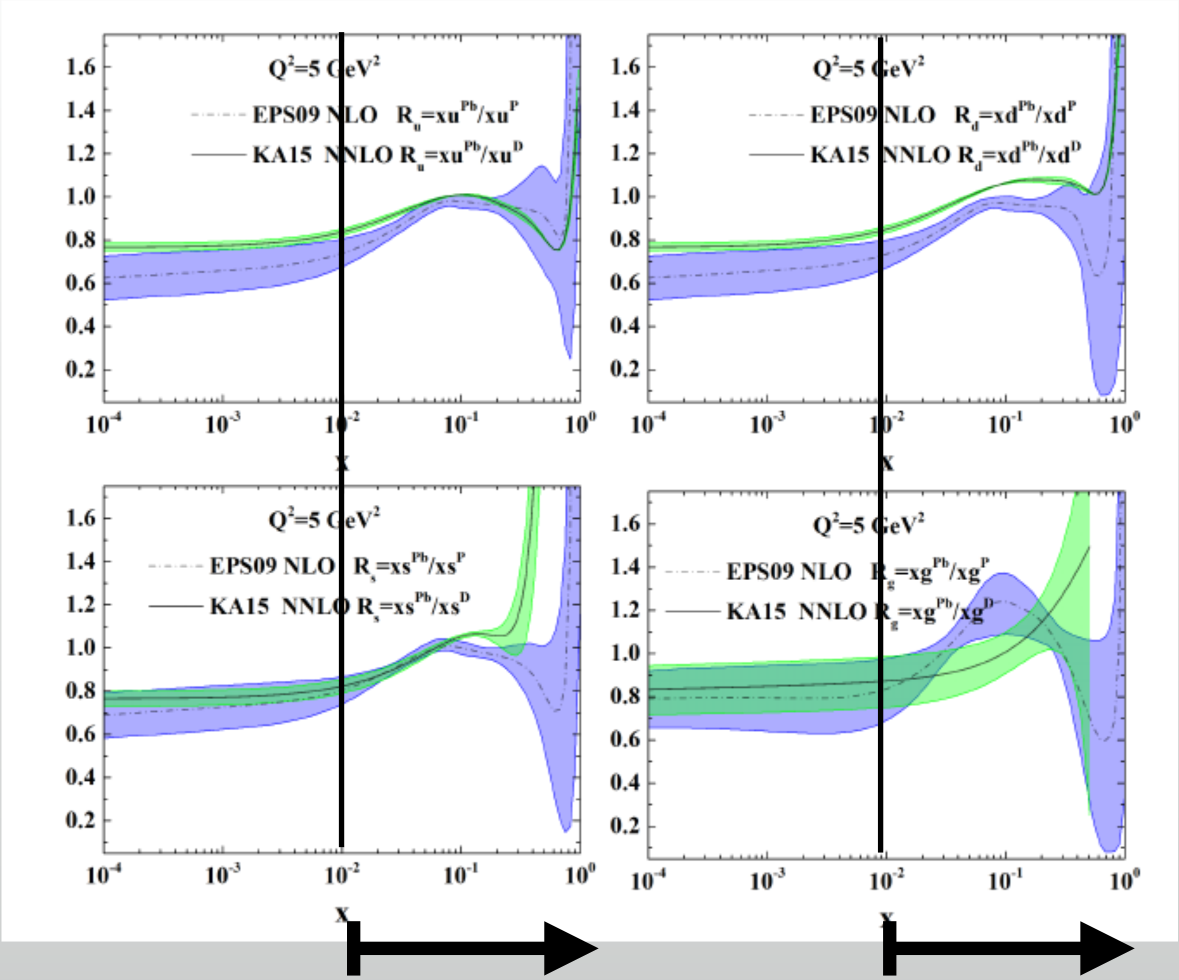

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Status and plans:

- LHC ran pPb collisions at 5.02 TeV/nucleon in 2012-2013.

ALICE: 31.94 nb^{-1}	ATLAS: 31.2 nb^{-1}	CMS: 31.69 nb^{-1}	LHCb: 2.12 nb^{-1}

➜ Jets and EW bosons: at present used to test factorisation in pA/AA, and they offer some constrains to nPDFs.
➜ No sizeable in-medium effects e.g. energy loss.
➜ Delicate centrality issues!!!

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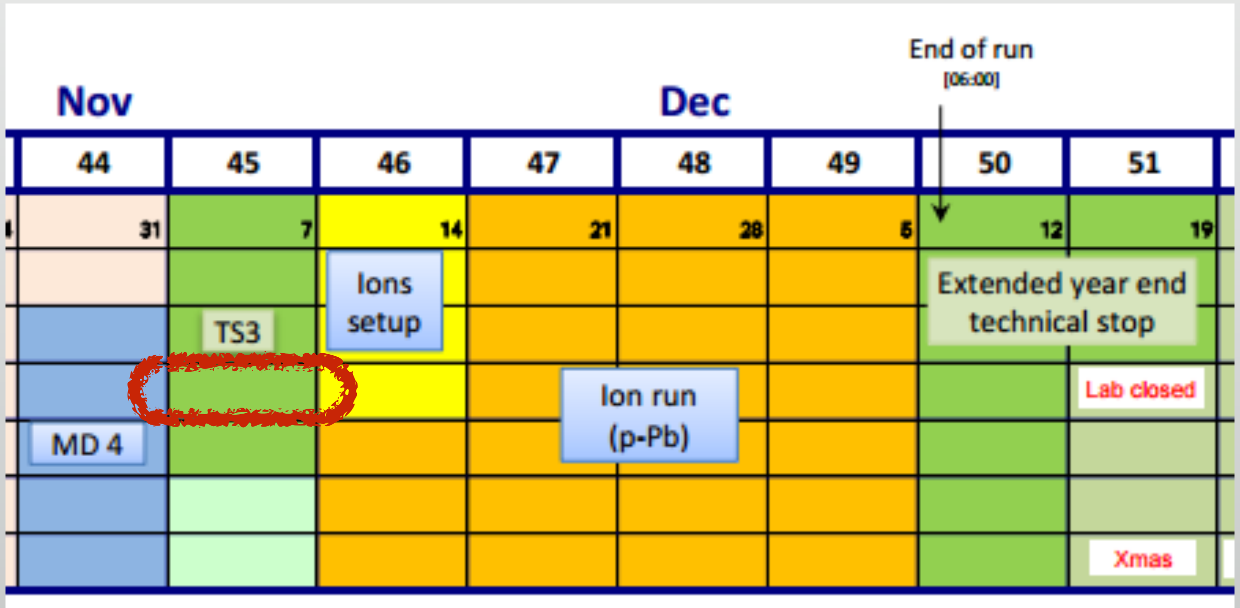
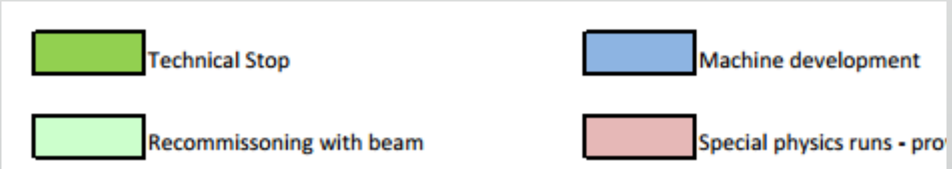


J. Jowett at IS2016



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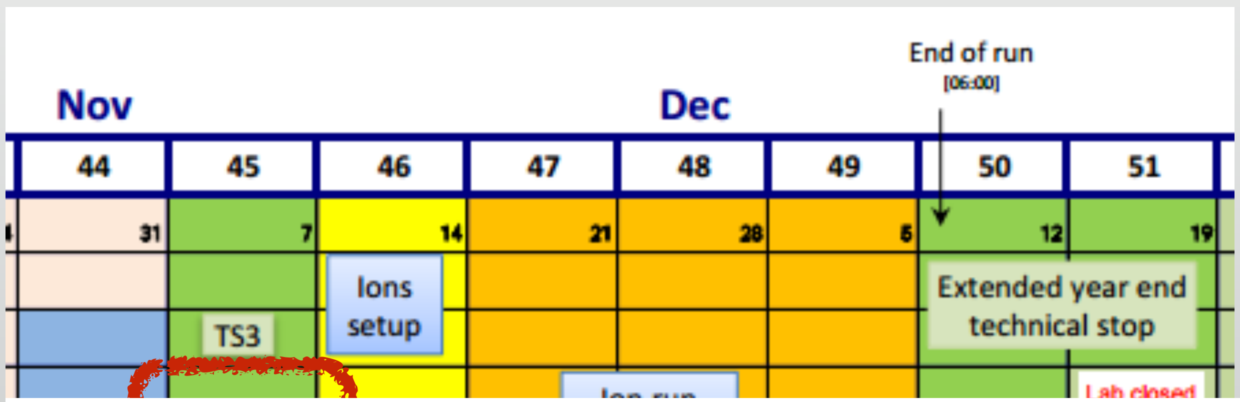

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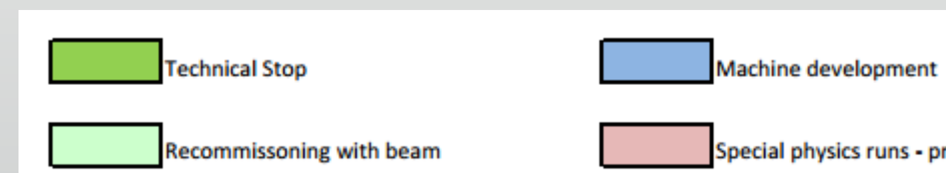

Proposed scheme – part-1

- Start with 5 TeV run
  - Less risk(low luminosity running, non-aggressive optics)
  - Hope to complete 5 TeV physics programme in short time
- Stop 5 TeV run when any of these criteria are met:
  - After 1B events delivered to ALICE
  - If by end of day-9 ≥700M events delivered
  - If the above criteria have not been met, continue the run till 700M events are delivered, unless this appears to significantly delay the start of the 8 TeV run
- During 5 TeV run
  - Protons in beam-1 / Moderate squeeze in ALICE (~3m)
  - Very long fills (~20hrs) luminosity leveled to 10^{28} cm^{-2} s^{-1} in ALICE
  - Can try to have very low luminosity collisions in other IPs (luminosity<10^{27} cm^{-2} s^{-1}) but stop this if any problems encountered

Disclaimer: We should leave some flexibility to change some of the cut-off numbers / dates, depending on the actual situation. With the goal of giving the best physics output of all parts of the programme.

Proposed scheme – part-2

- Default strategy for 8 TeV run
  - Moderate squeeze in ALICE (~3m) / LHCb (~2m)
  - ATLAS/CMS pp optics (40cm) or slight de-squeeze
    - To be determined by machine experts after more studies
  - Beam reversal
- If significantly behind expectation drop beam reversal (this would save ~2 days)
  - e.g. if <25/nb delivered to ATLAS/CMC by end of day-19
- Fills optimized to give luminosity to ATLAS/CMS
  - Short fills (~5hrs)
- Expectation (assuming no significant down time):
  - ~70/nb for ATLAS/CMS (~5.5/nb per ~5hr fill with 5hr turn-around time)
  - ~10/nb each for ALICE/LHCb* (less than requested)
  - (* For LHCb this depends on exact filling schemes, which in turn depend on various kicker magnet rise-times which have not been measured yet).

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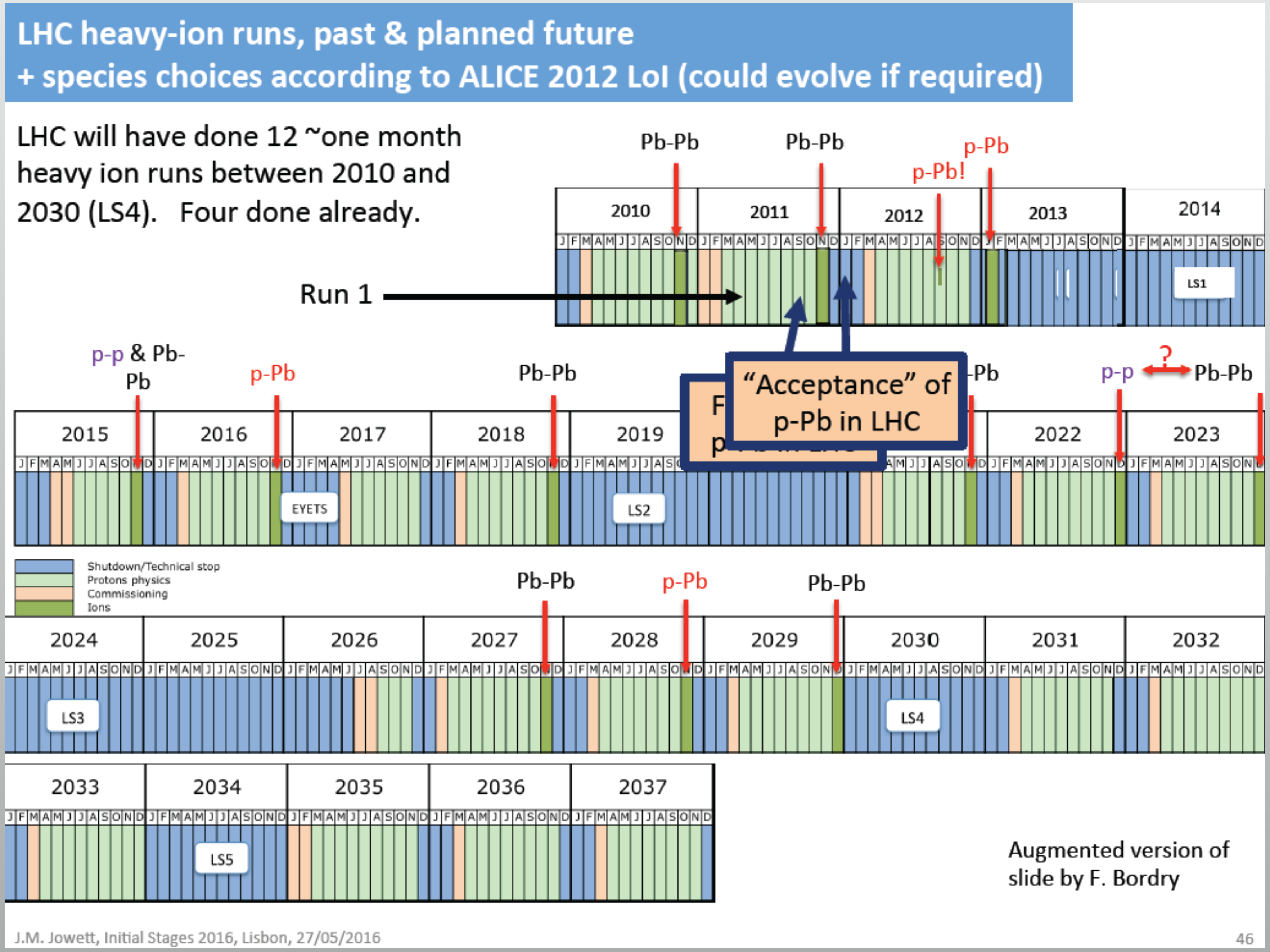
- According to current plans, LHC will not run pPb again until 2028.



Impact of pPb:

• Reweighting (1512.01528) of EPS09 and DSSZ (with CT10 and MSTW2008) including 165 **pPb data @ LHC**:

➜ W's from ALICE ($A_{F/B}$) and CMS ($A_{F/B}$ and A_C).
➜ Z's ($A_{F/B}$) from ATLAS and CMS.
➜ Jets from ATLAS ($A_{F/B}$).
➜ Dijets from CMS.
➜ (Even) $h^{\pm}$ from ALICE ($A_{B/C}$) and CMS ($A_{F/B}$) (p_T>5 GeV, DSS FFs).

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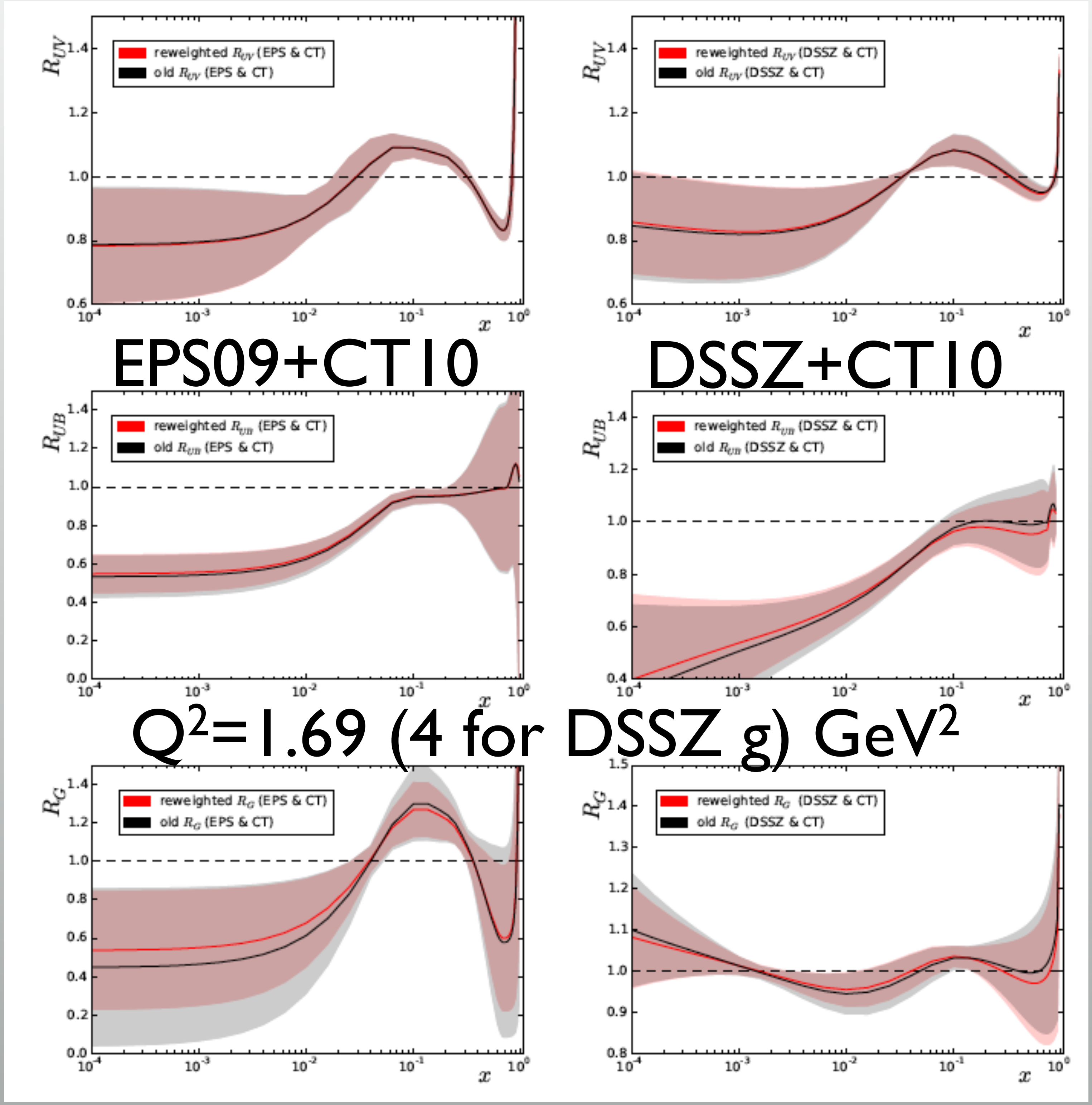

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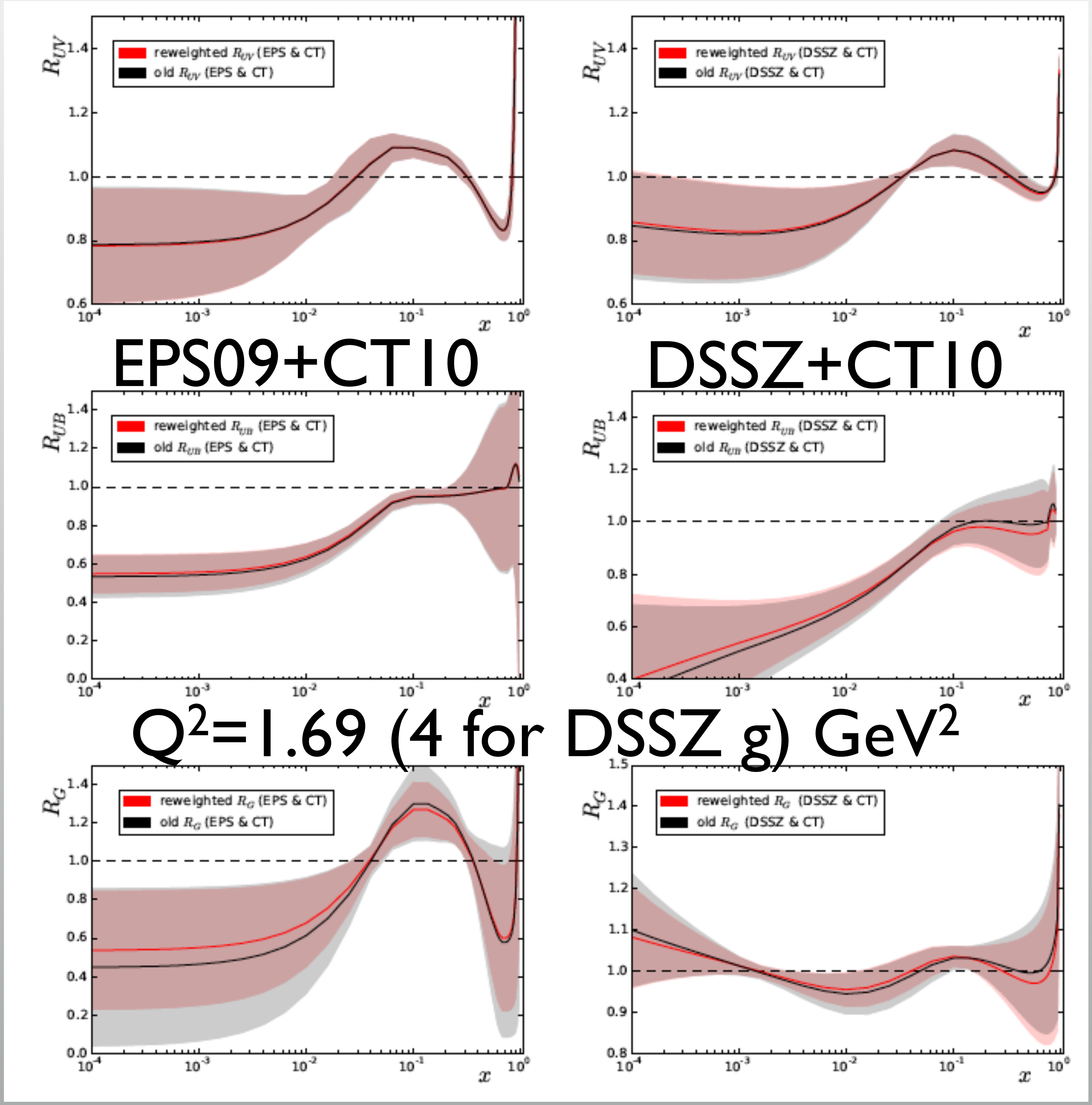

- All in all, the effect of LHC data is rather mild.
- Dijets are the most constraining, EW bosons the most promising to relax the initial condition $R_u=R_d$.
- Link PDF - nPDF clearly visible.
- Take care with extrapolations!!!

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All data	PDF + nPDF	χ^2_{original}	$\chi^2_{\text{reweighted}}$	N_{eff}
	CT10+DSSZ	1.074	1.016	9044
	CT10+EPS09	0.674	0.632	8657
	MSTW2008+DSSZ	0.876	0.826	9128
N_{rep}=10000	MSTW2008+EPS09	0.649	0.583	8585
	CT10 only	1.425	-	-
	MSTW2008 only	1.138	-	-

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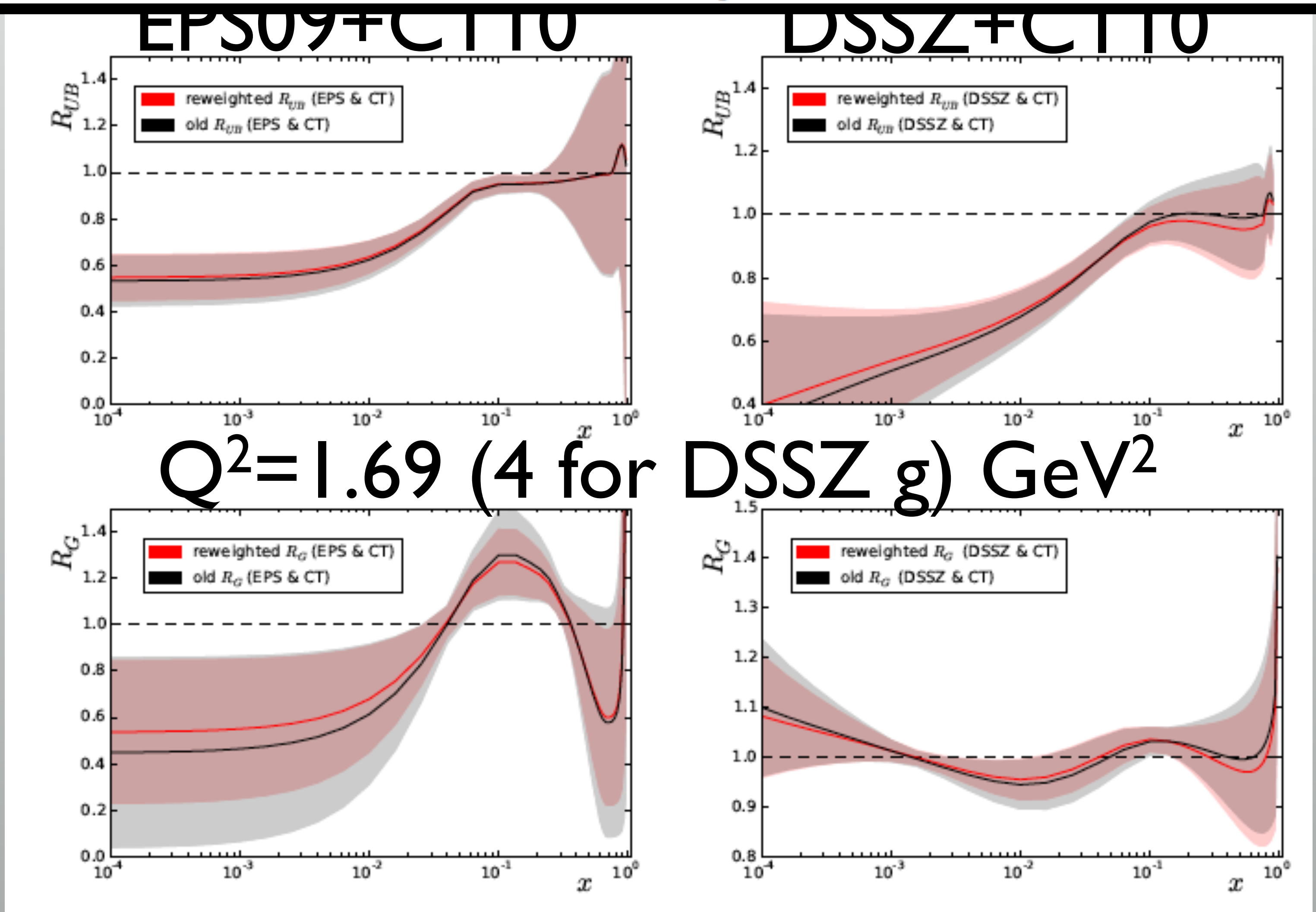
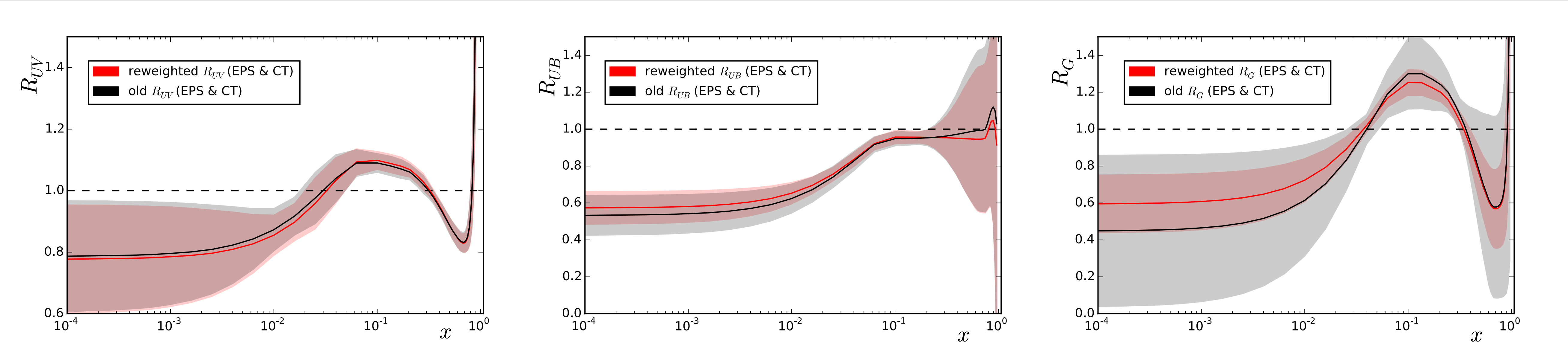


An exercise:

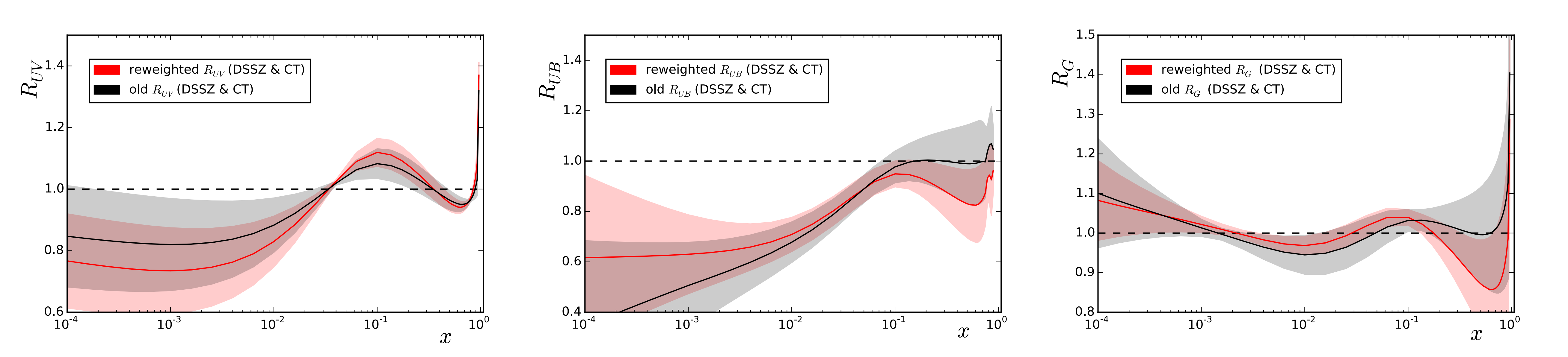
- Repeat the previous analysis but reducing the total error bars by a factor 3 (not for this year's run - factor 2 in statistics, same detectors; it might be possible for Run 4).

EPS09+CT10



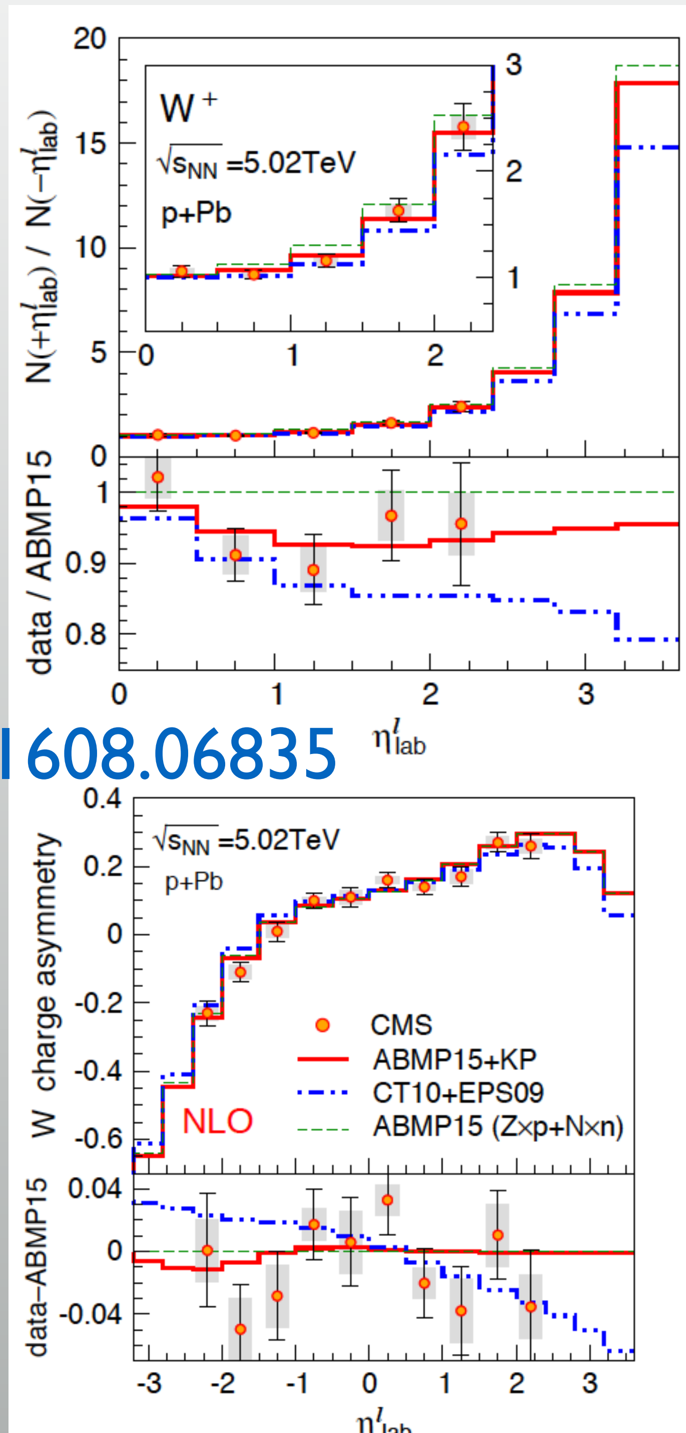
Q^2=1.69 (4 for DSSZ g) GeV^2

DSSZ+CT10

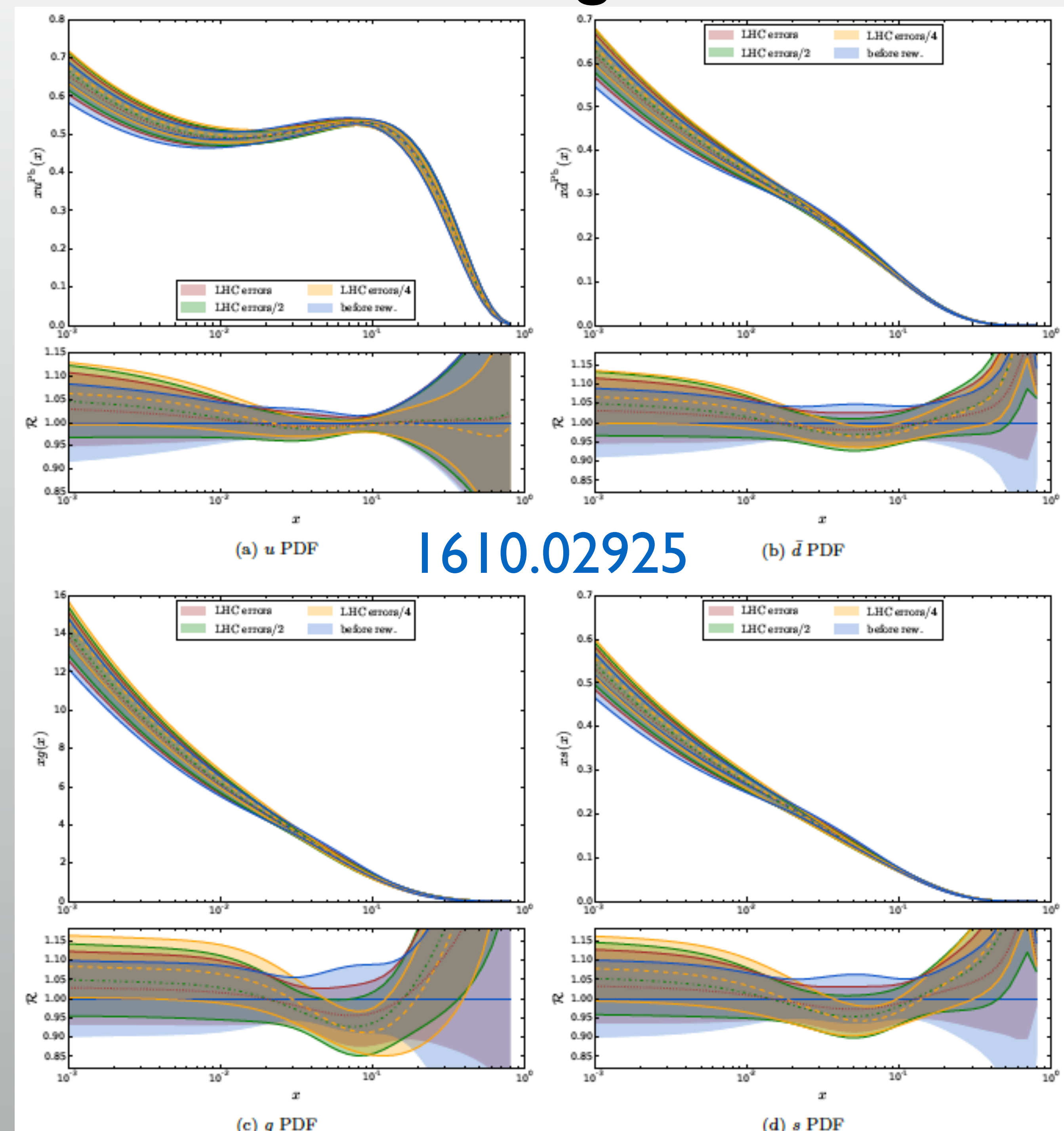


W's and Z's:

- Several studies address the flavour dependence of nuclear effects using EW bosons: sensitive to R_u/R_d at large x.



1608.06835



1610.02925

KP model

nCTEQ15, reweighting

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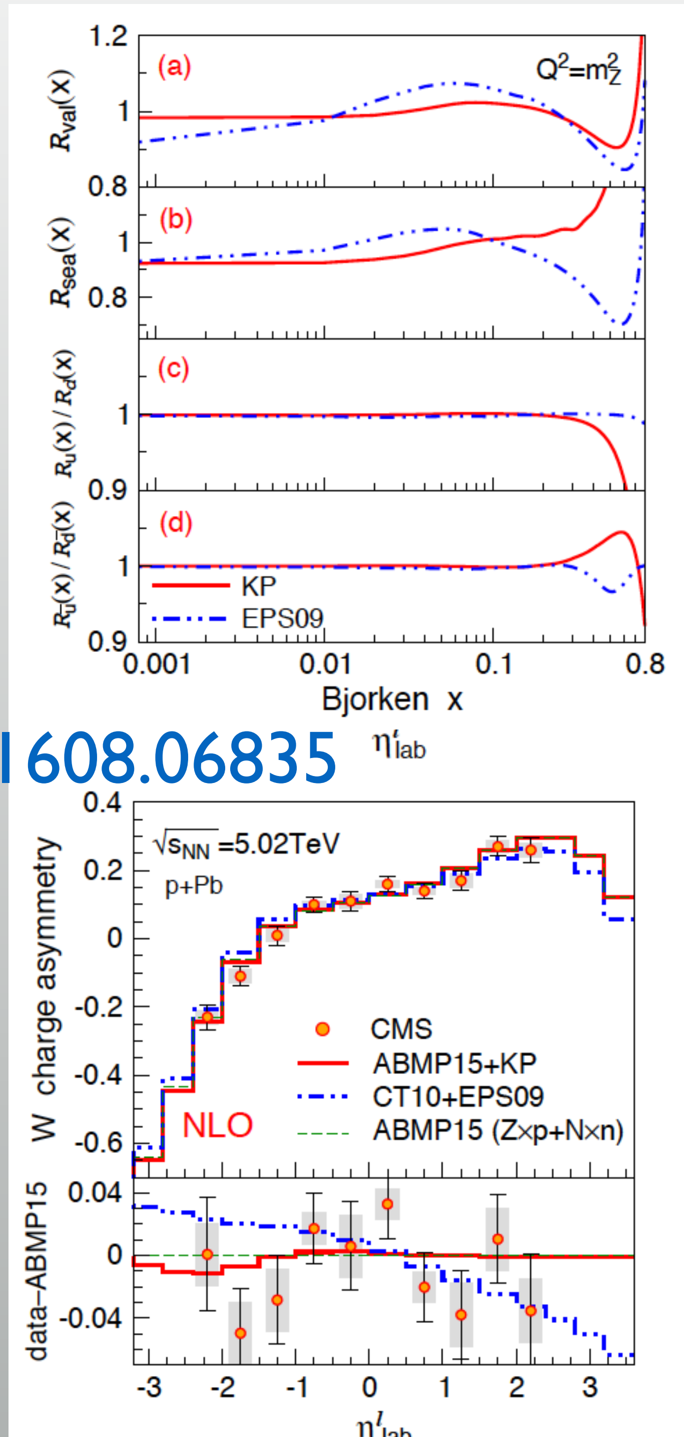

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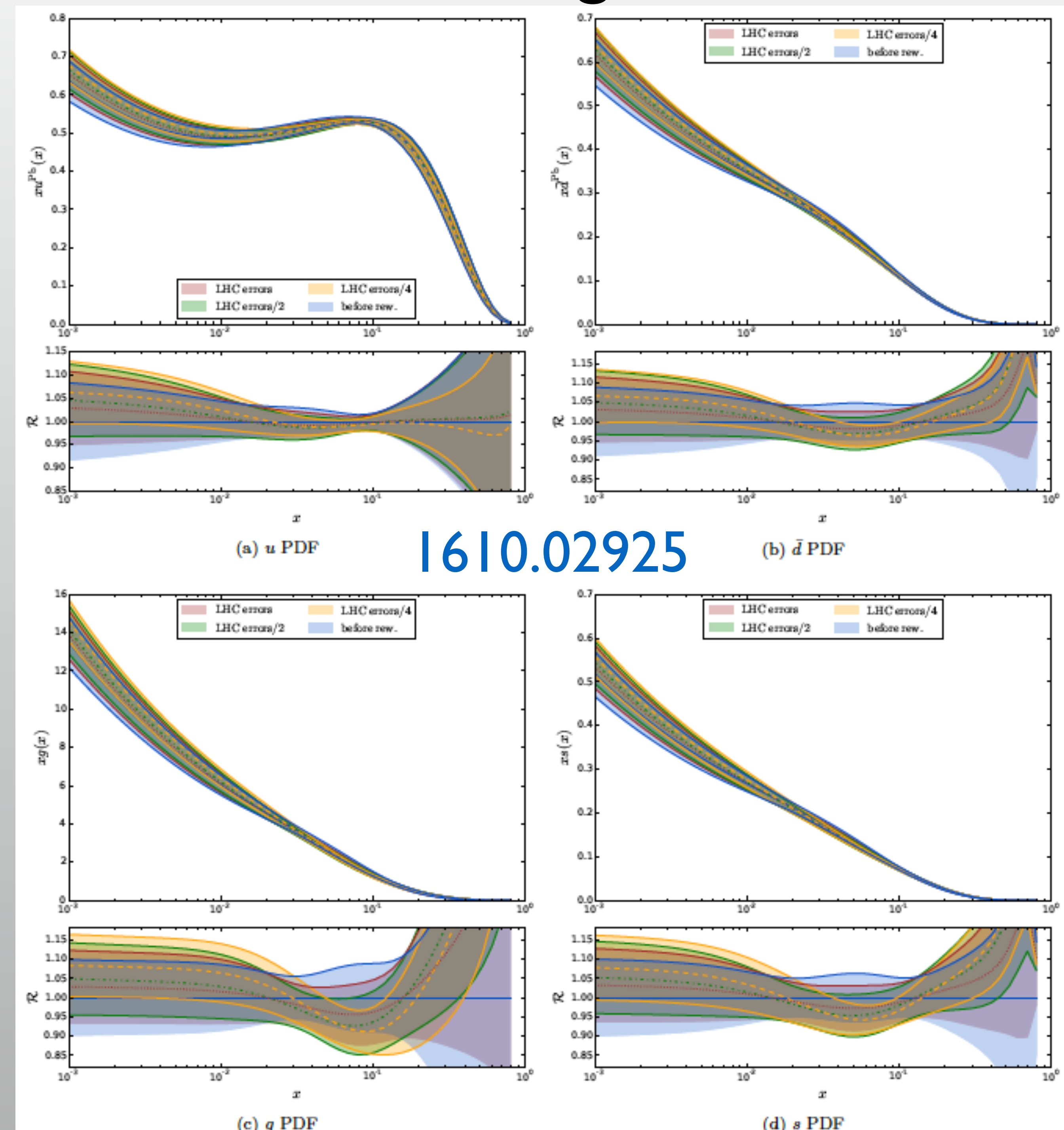

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nCTEQ15, reweighting

CMS dijets reanalysed:

- CMS dijets were the most constraining item (1408.4563), to substitute PHENIX pions for constraining the glue at x~0.01.
- New more differential analysis (CMS PAS HIN-16-003) show differences between PDF/nPDF sets.
- Impact to be evaluated: NNLO jets needed (1611.01460)?

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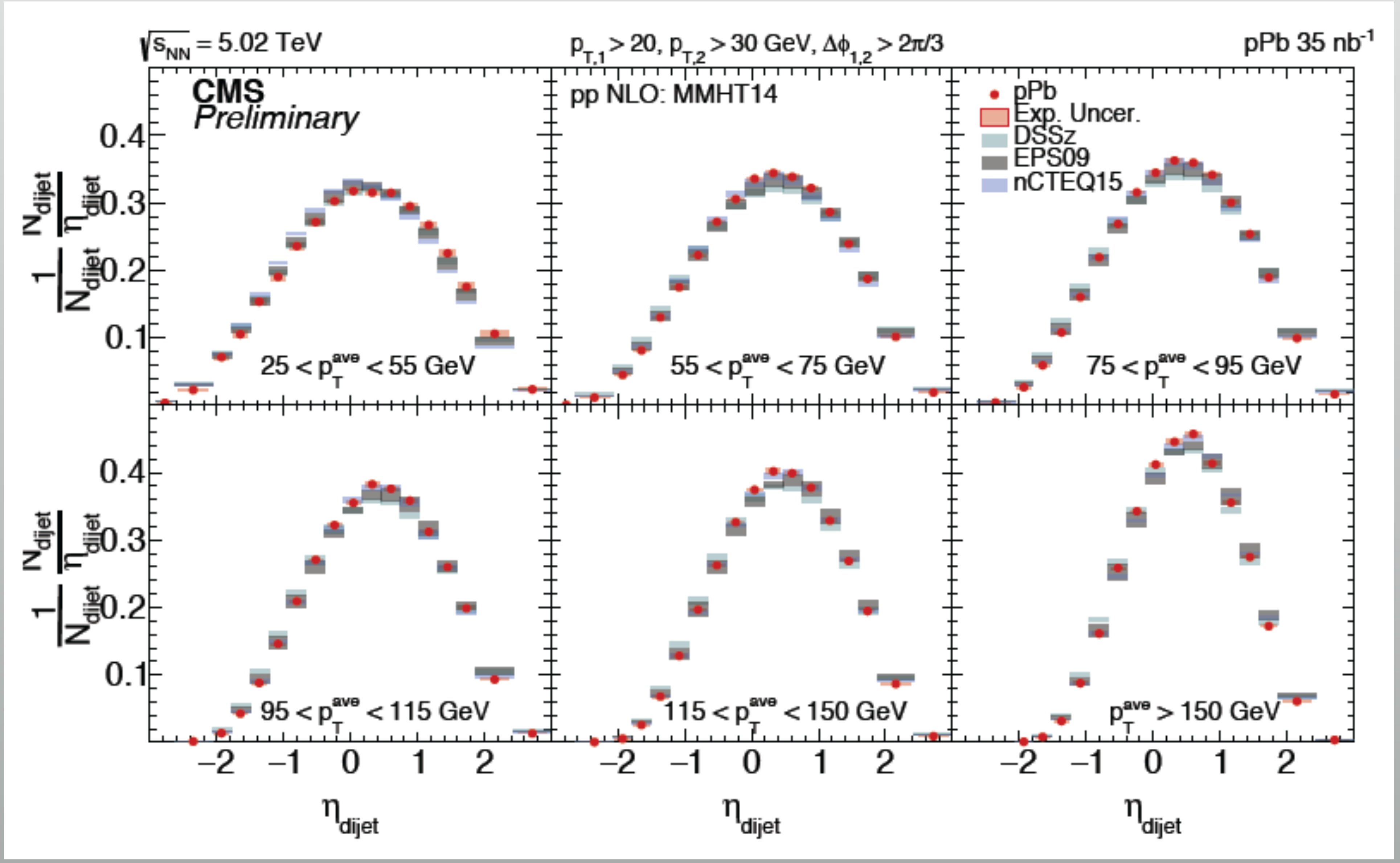
$p_T^{ave}=(p_{T,1}+p_{T,2})/2$



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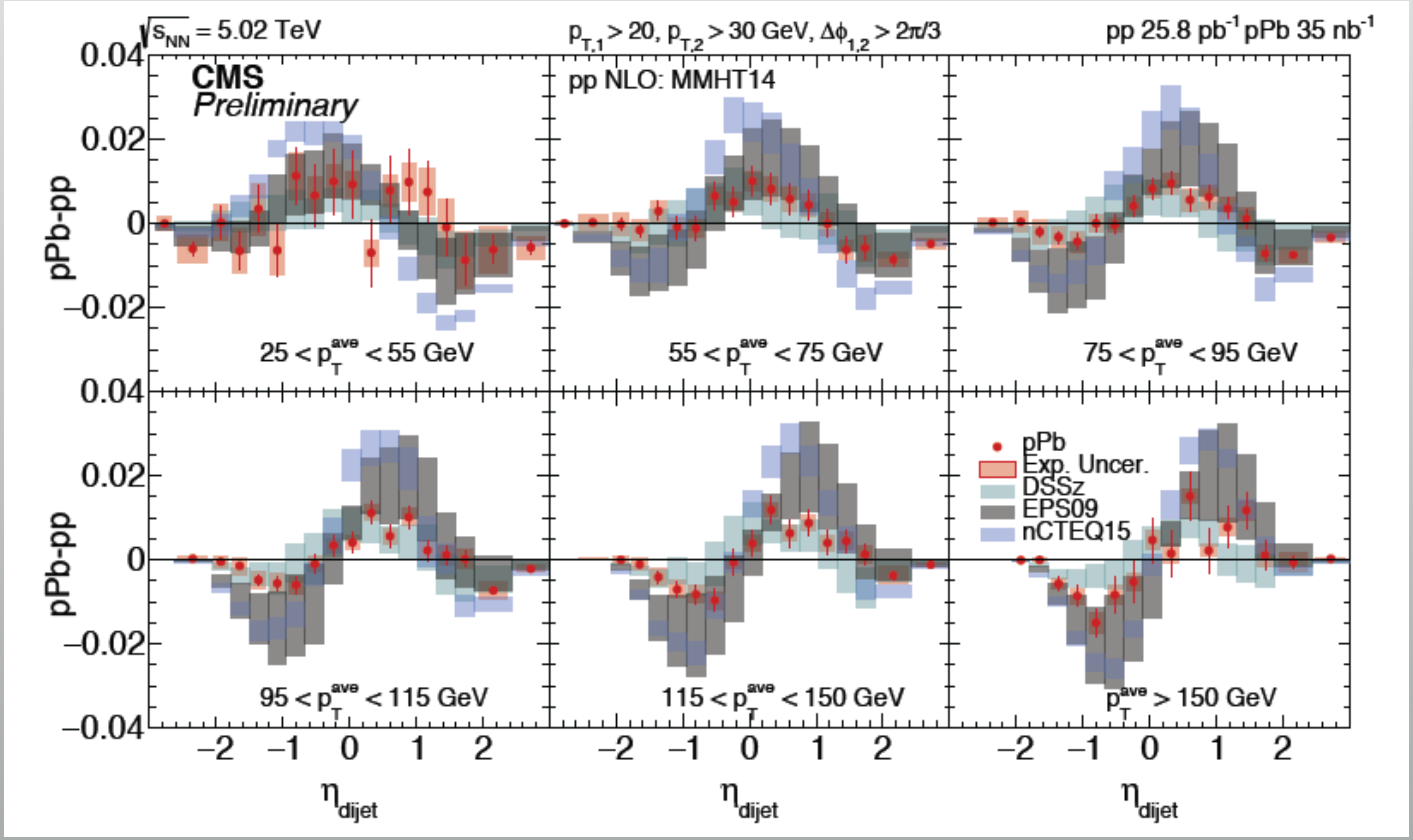

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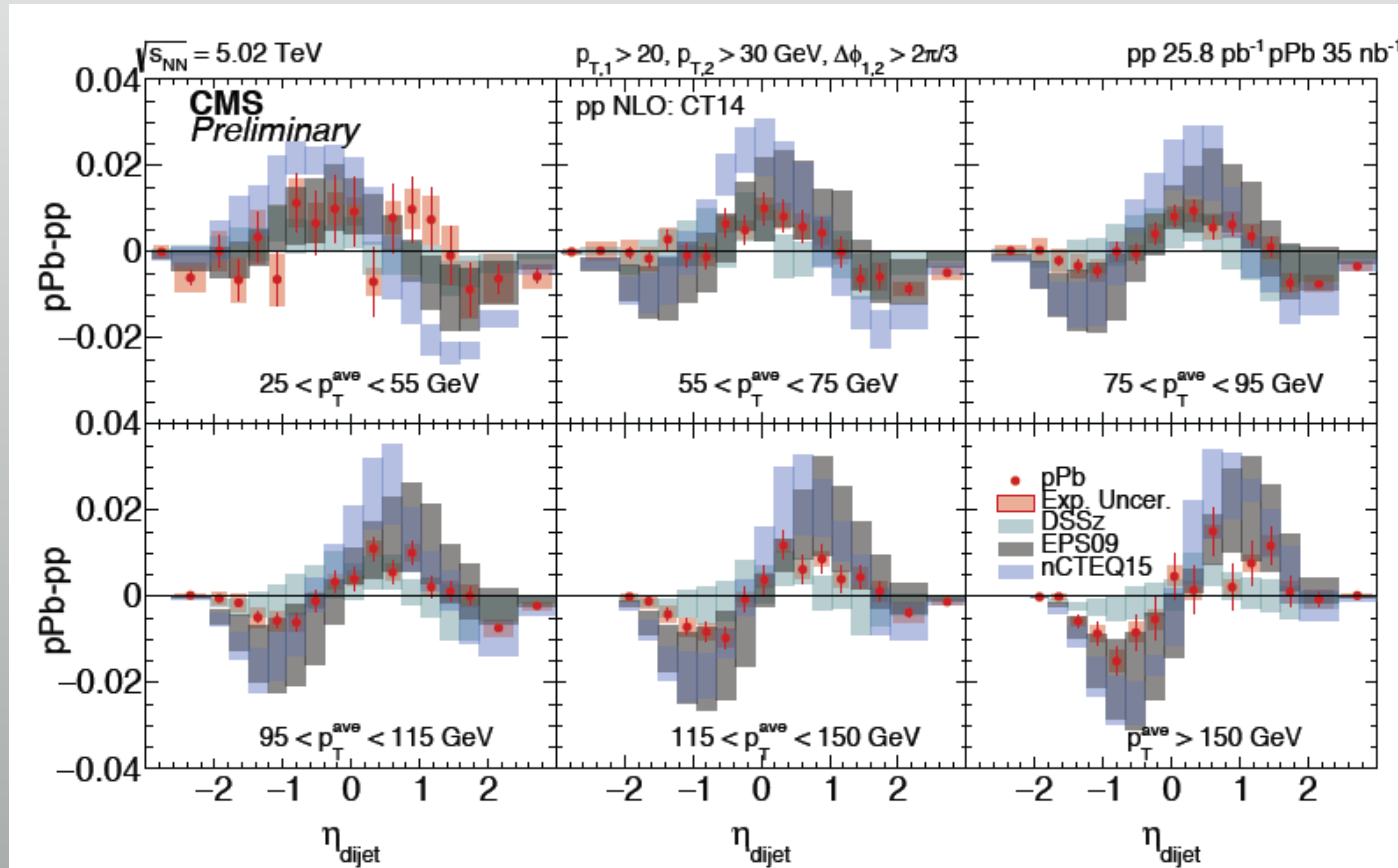

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- D's (combinations of spectra at 5, 7 and 13 TeV, 1610.09373) have been used to constrain the small-x glue in p, and similar proposals exist for using exclusive J/ψ in UPCs (1610.02272).
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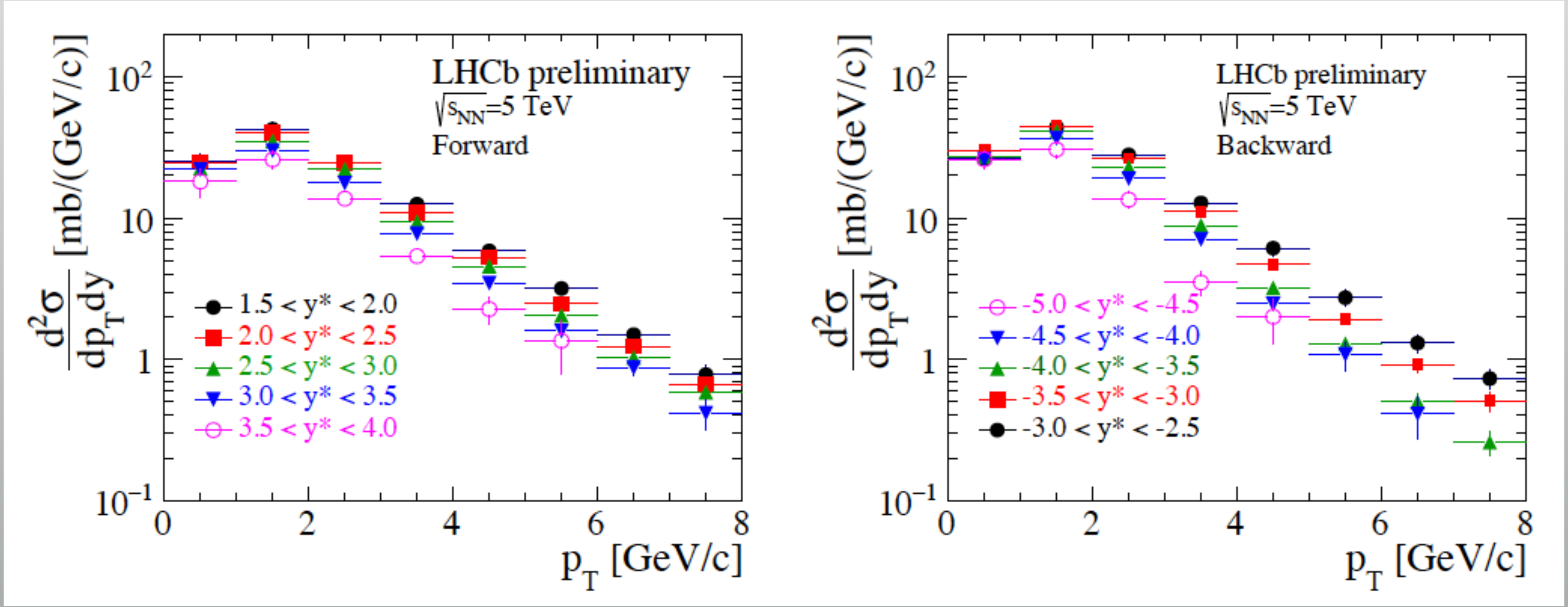

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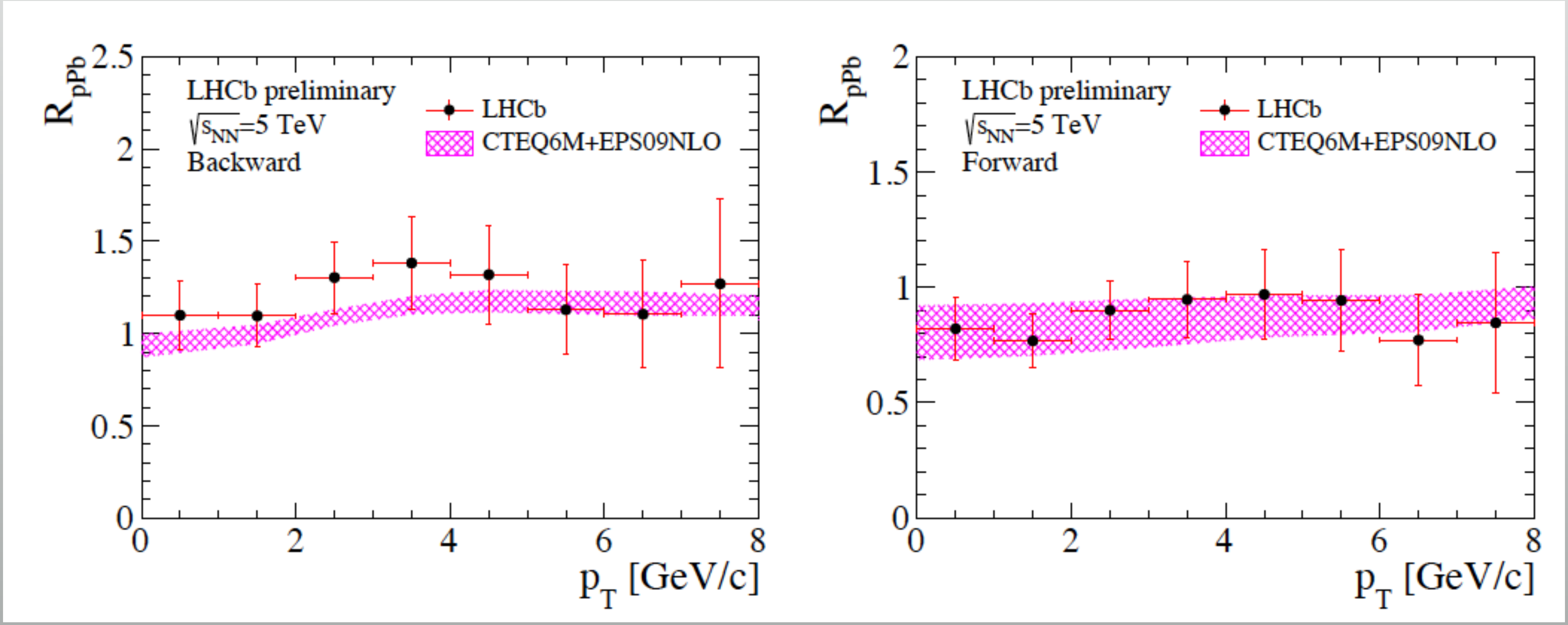

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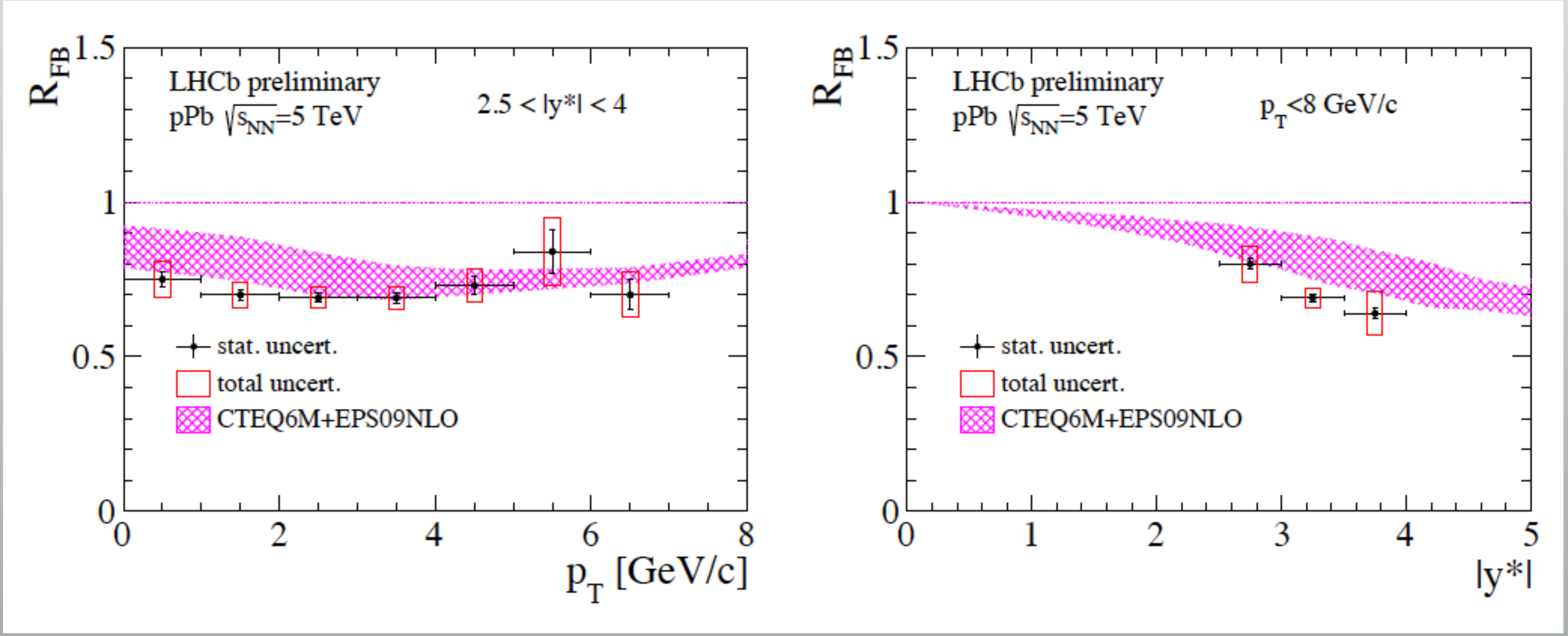

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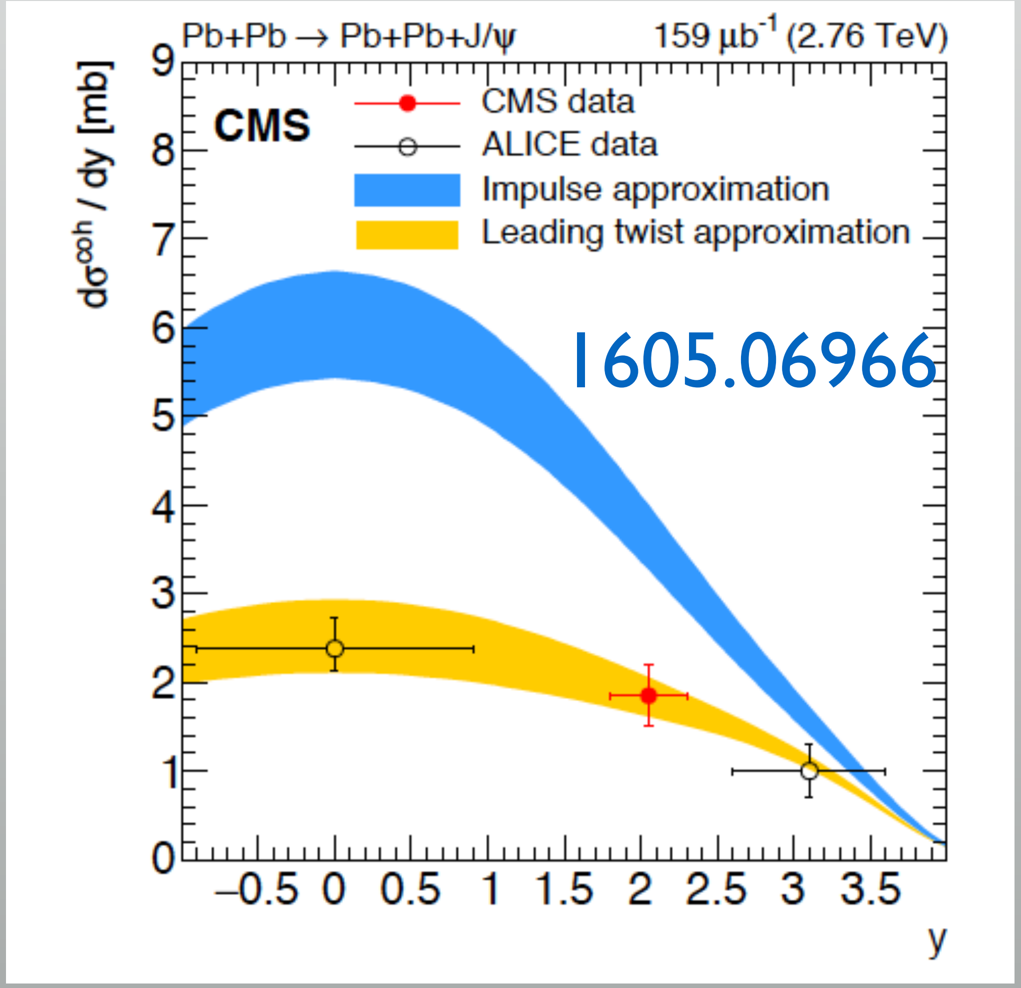
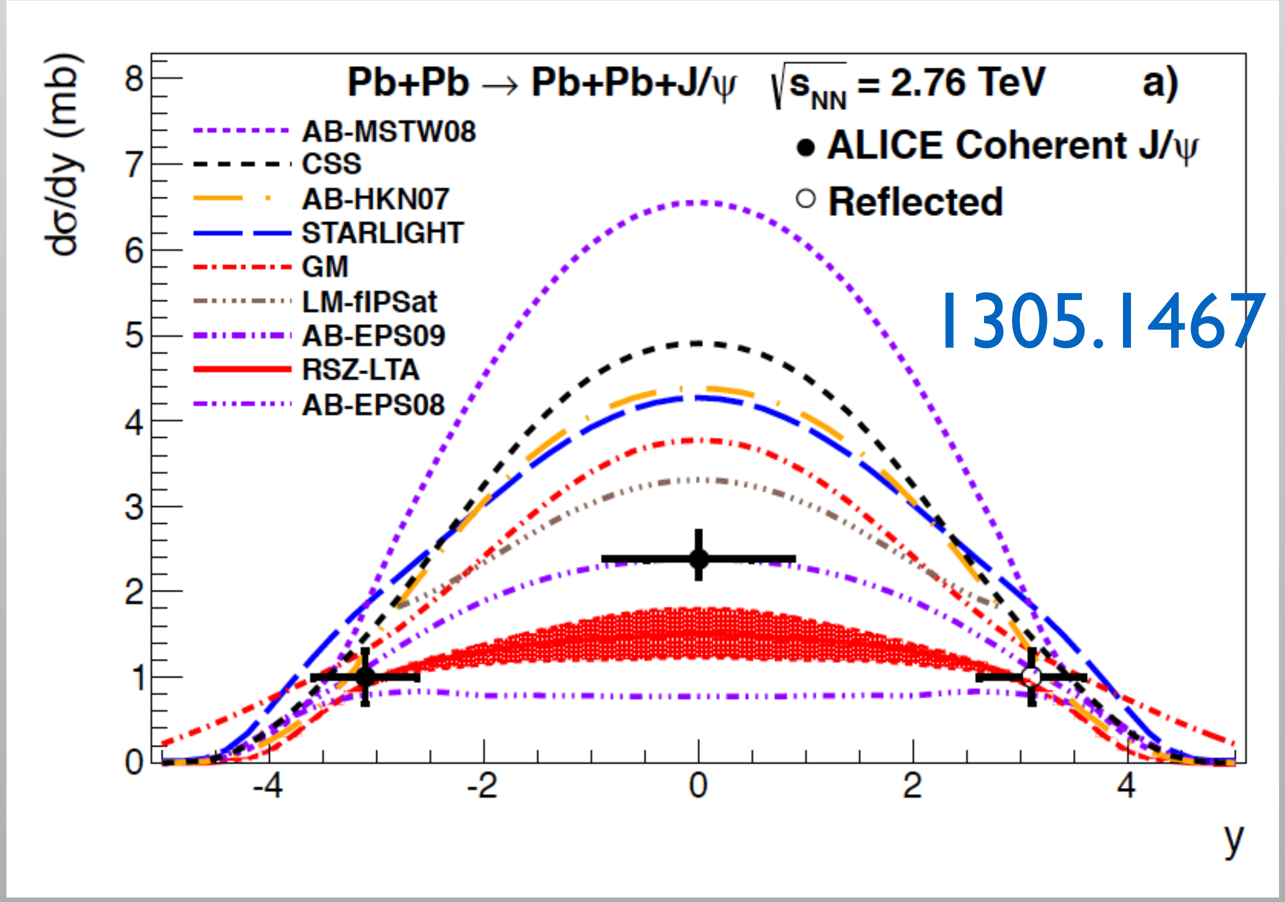
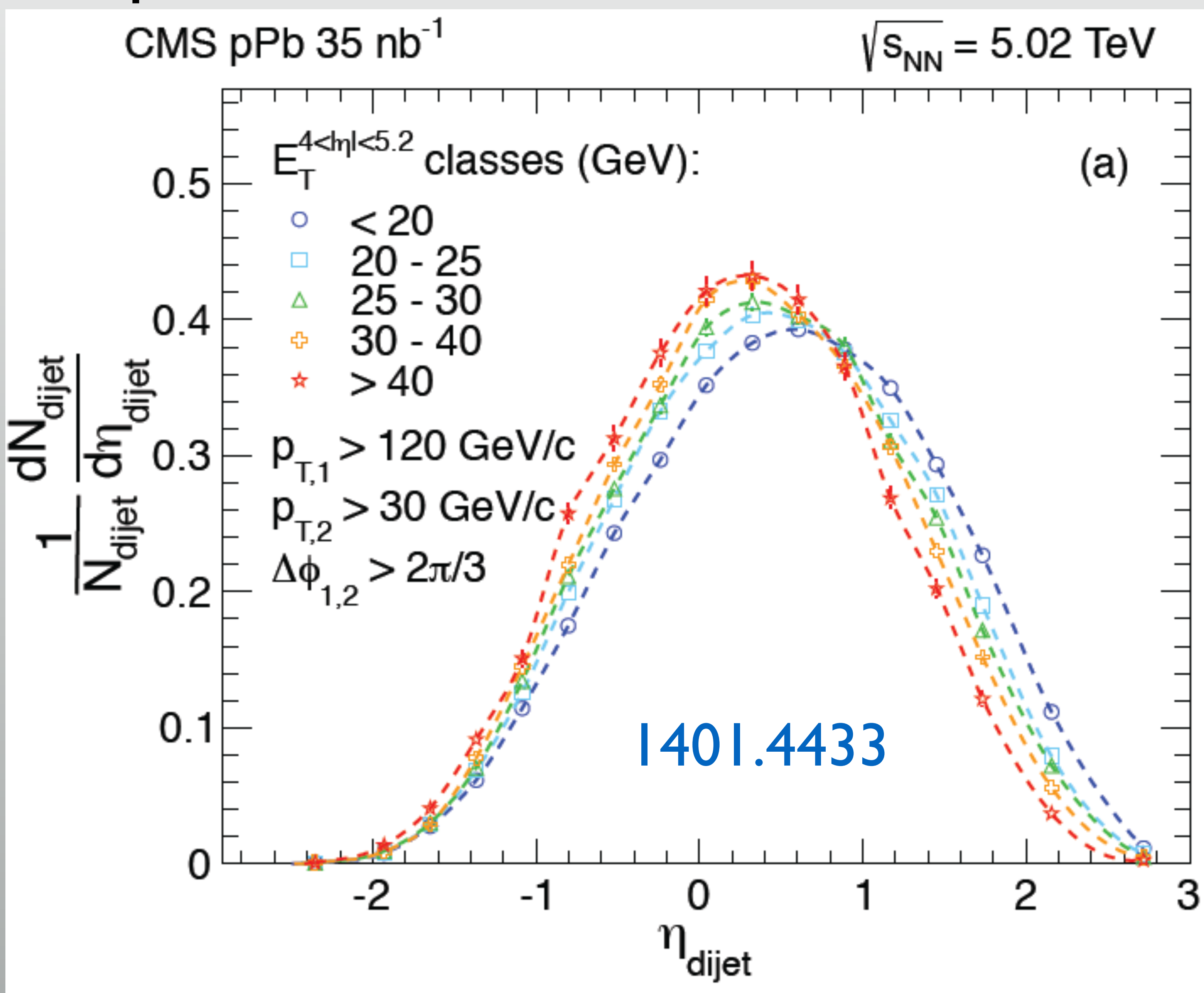
- D^0 mesons in pPb from LHCb (LHCb-CONF-2016-003, not yet using 5 TeV pp data) look compatible with collinear factorisation.
- J/ψ production in UPCs indicates gluon shadowing at small x.





Centrality:

- Centrality studies in pPb are problematic: CMS dijets, ATLAS and PHENIX jets, J/ψ,… (ALICE ZDC probably the best option).
- Coupling of soft and hard production, included in models, is able to reproduce the trends in data, see the talk by Milhano in HP2015.



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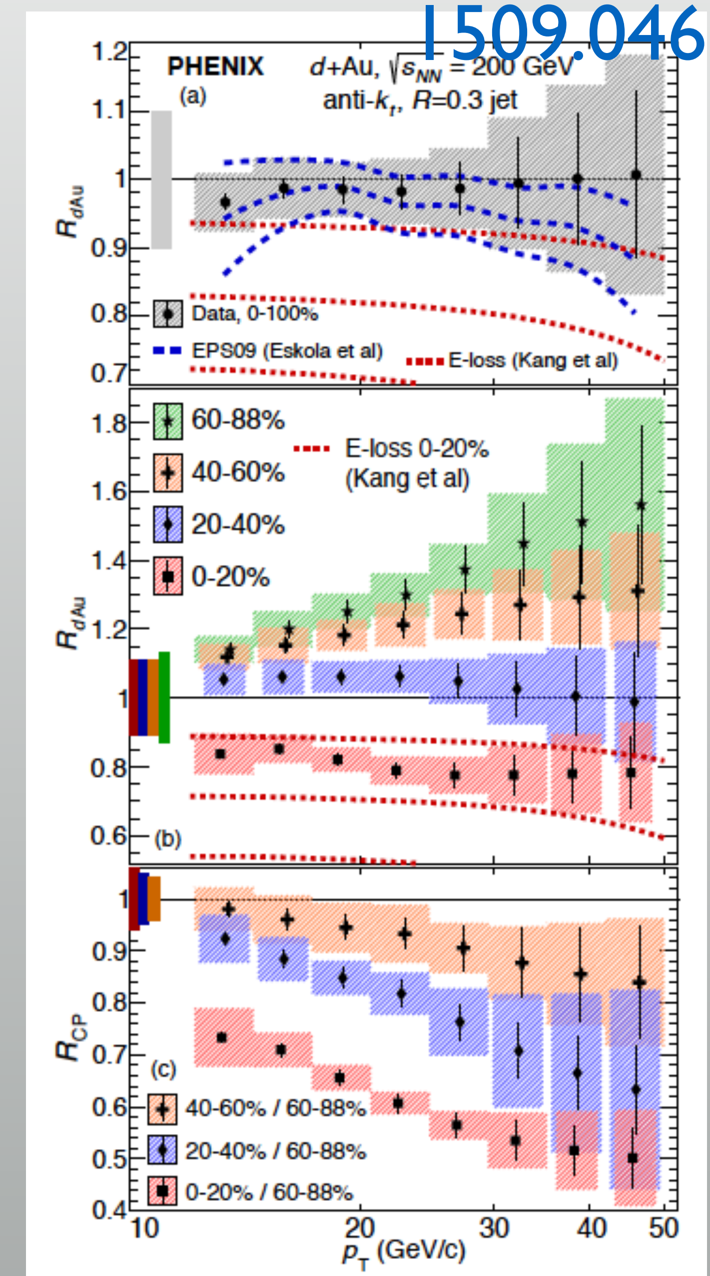

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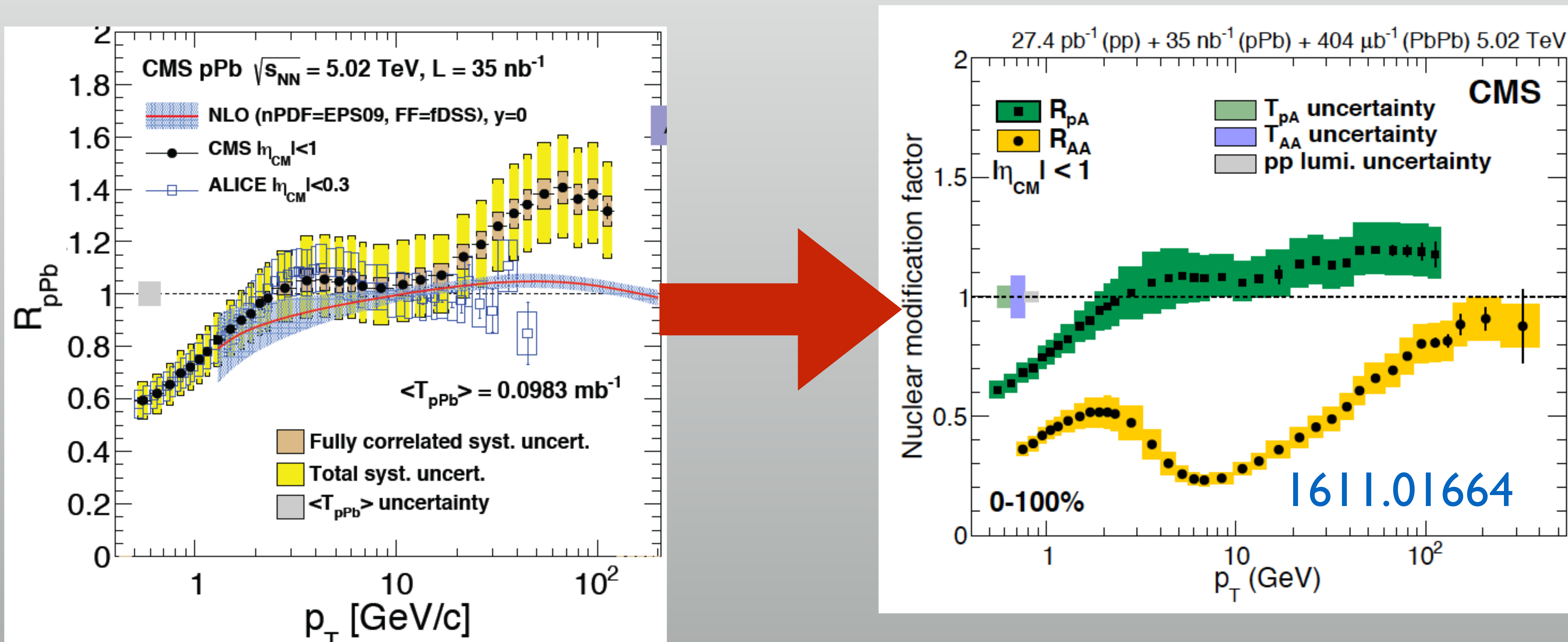

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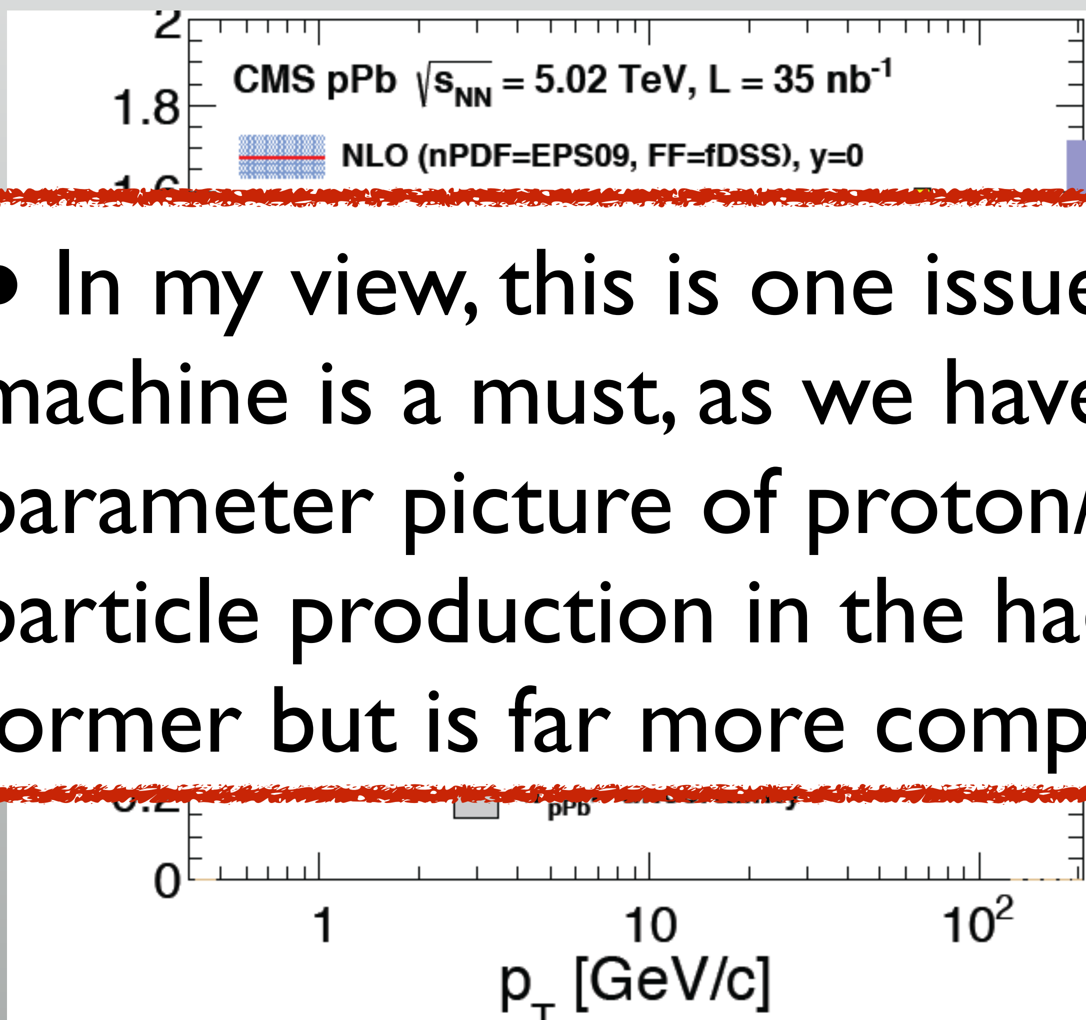
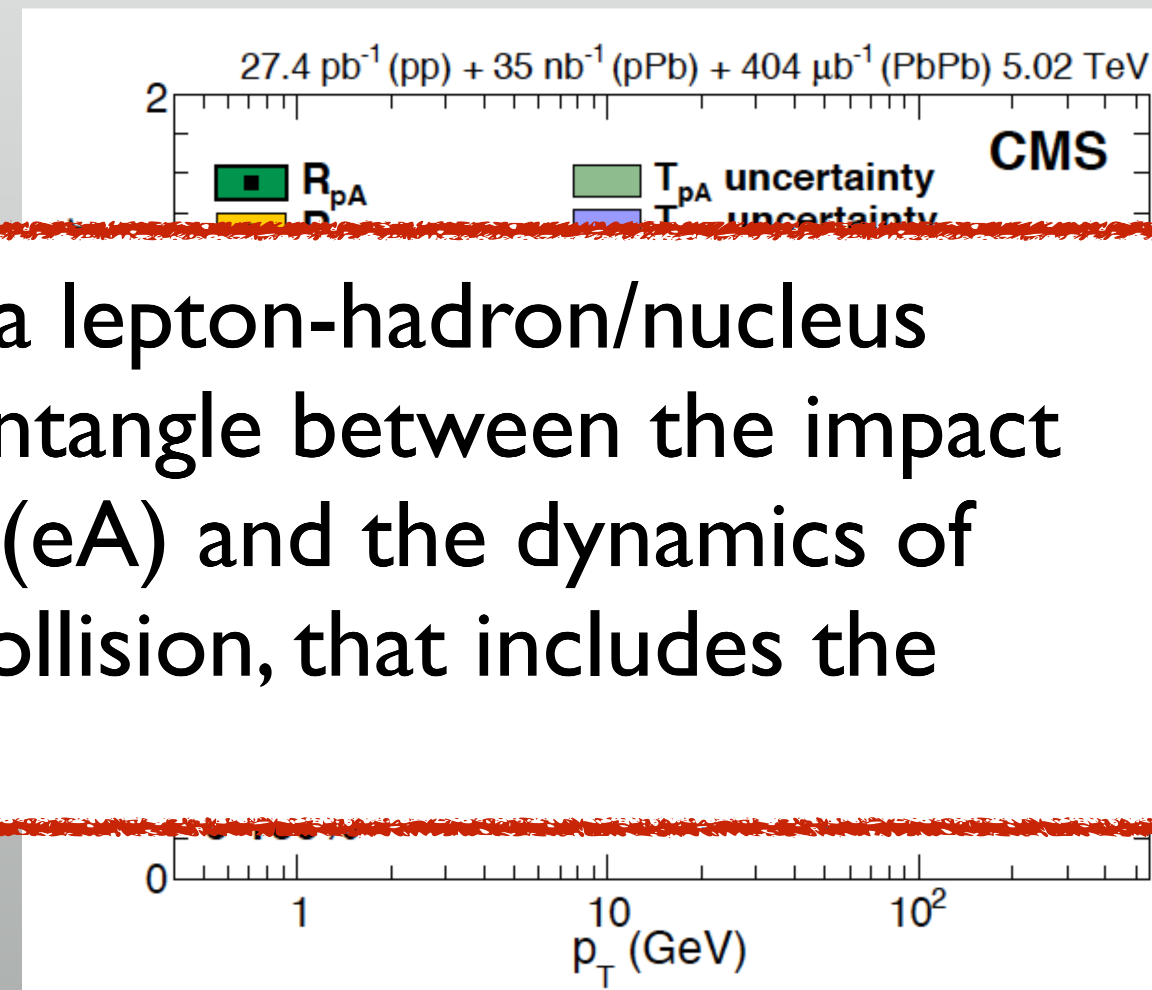
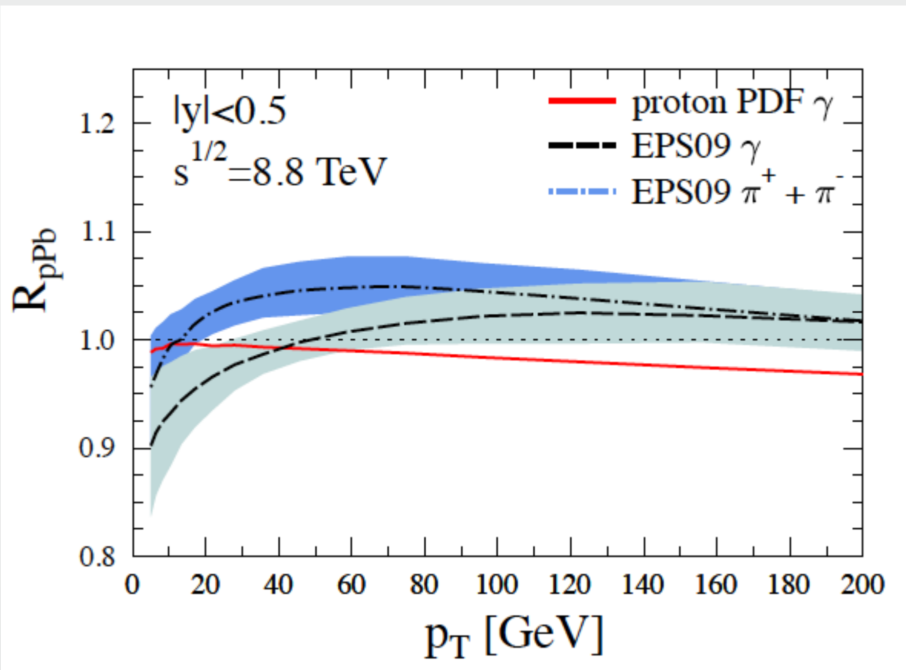




- In my view, this is one issue where a lepton-hadron/nucleus machine is a must, as we have to disentangle between the impact parameter picture of proton/nucleus (eA) and the dynamics of particle production in the hadronic collision, that includes the former but is far more complex.

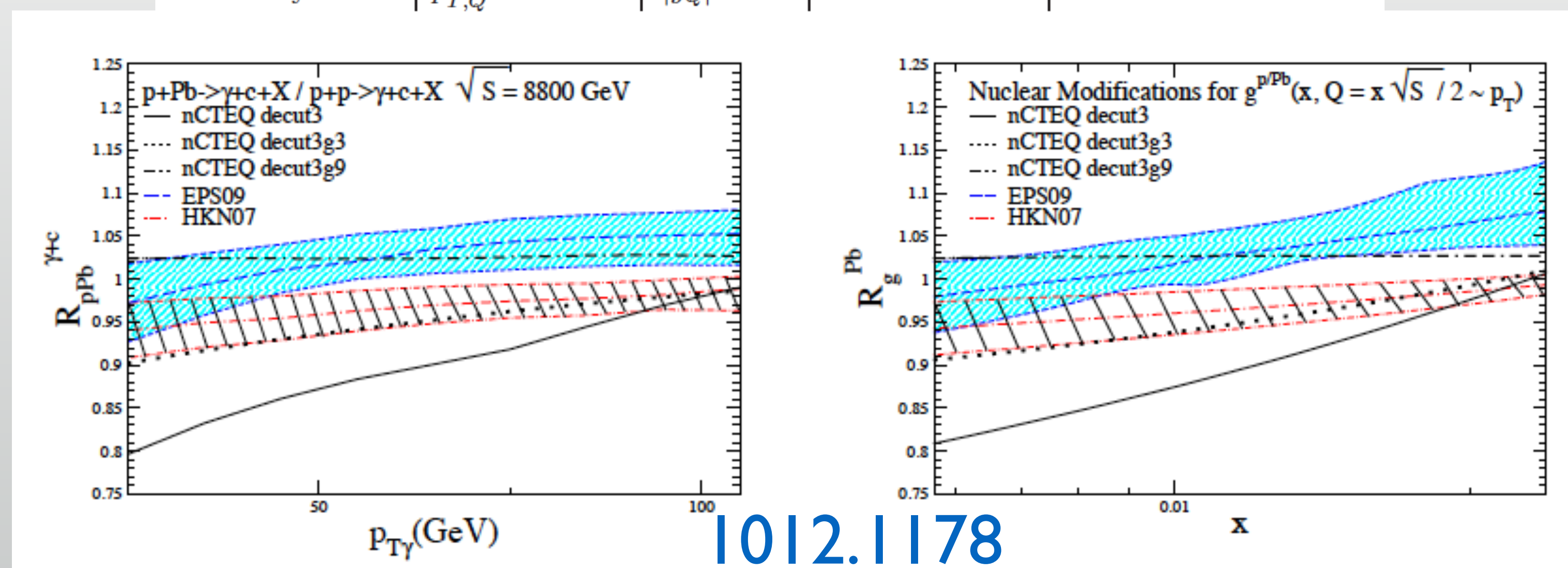
Other possibilities:

- Forward photons (LHCb, ALICE FoCal), photon+HQ, pion-nucleus DY data,…, have been proposed.



1103.1471

	p_T	Rapidity	ϕ	Isolation Cuts
Photon (PHOS)	$p^{min}_{T,\gamma} = 20$ GeV	$\lvert y_\gamma \rvert < 0.12$	$220° < \phi < 320°$	$R = 0.2$, $p_T^{th} = 2$ GeV
Photon (EMCal)	$p^{min}_{T,\gamma} = 20$ GeV	$\lvert y_\gamma \rvert < 0.7$	$80° < \phi < 180°$	$R = 0.2$, $p_T^{th} = 2$ GeV
Heavy Jet	$p^{min}_{T,Q} = 15$ GeV	$\lvert y_Q \rvert < 0.7$	——	——



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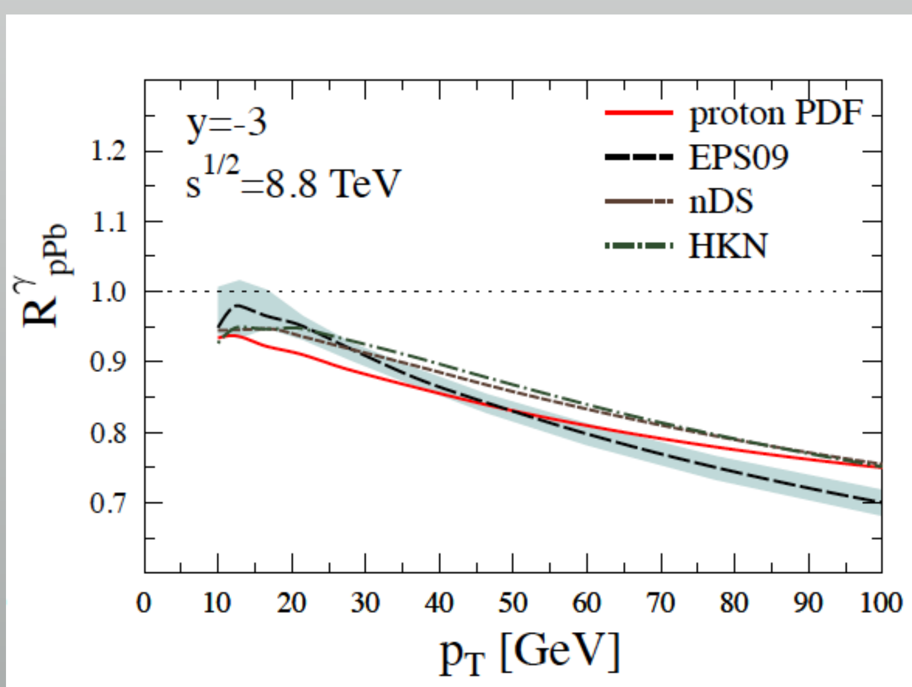
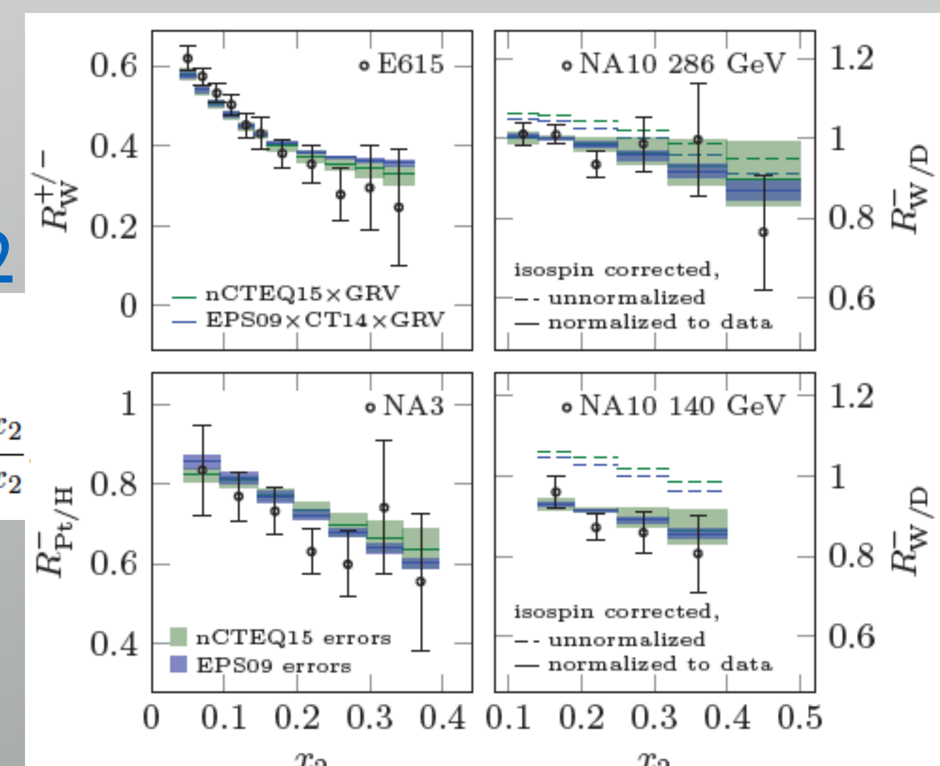


1609.07262

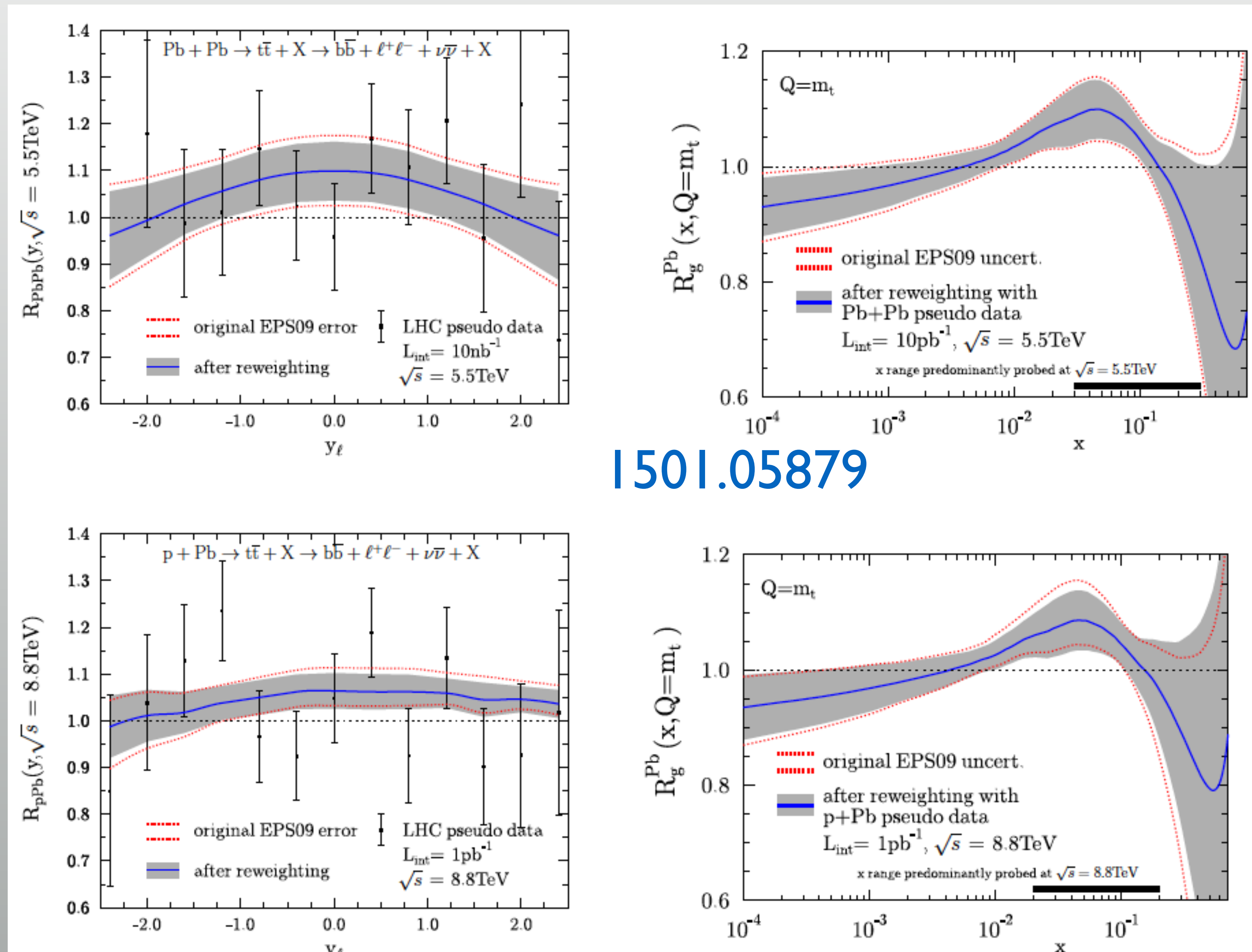
$$R_A^{+/-}(x_2) \equiv \frac{d\sigma(\pi^+ + A \to l^- l^+ + X)/dx_2}{d\sigma(\pi^- + A \to l^- l^+ + X)/dx_2},$$

$$R^-_{A_1/A_2}(x_2) \equiv \frac{\frac{1}{A_1} d\sigma(\pi^- + A_1 \to l^- l^+ + X)/dx_2}{\frac{1}{A_2} d\sigma(\pi^- + A_2 \to l^- l^+ + X)/dx_2}$$



Other possibilities:

- Forward photons (LHCb, ALICE FoCal), photon+HQ, pion-nucleus DY data,…, have been proposed.
- Top may be available for Run 4 (and for FCC).



1501.05879

Contents:

1. Introduction.

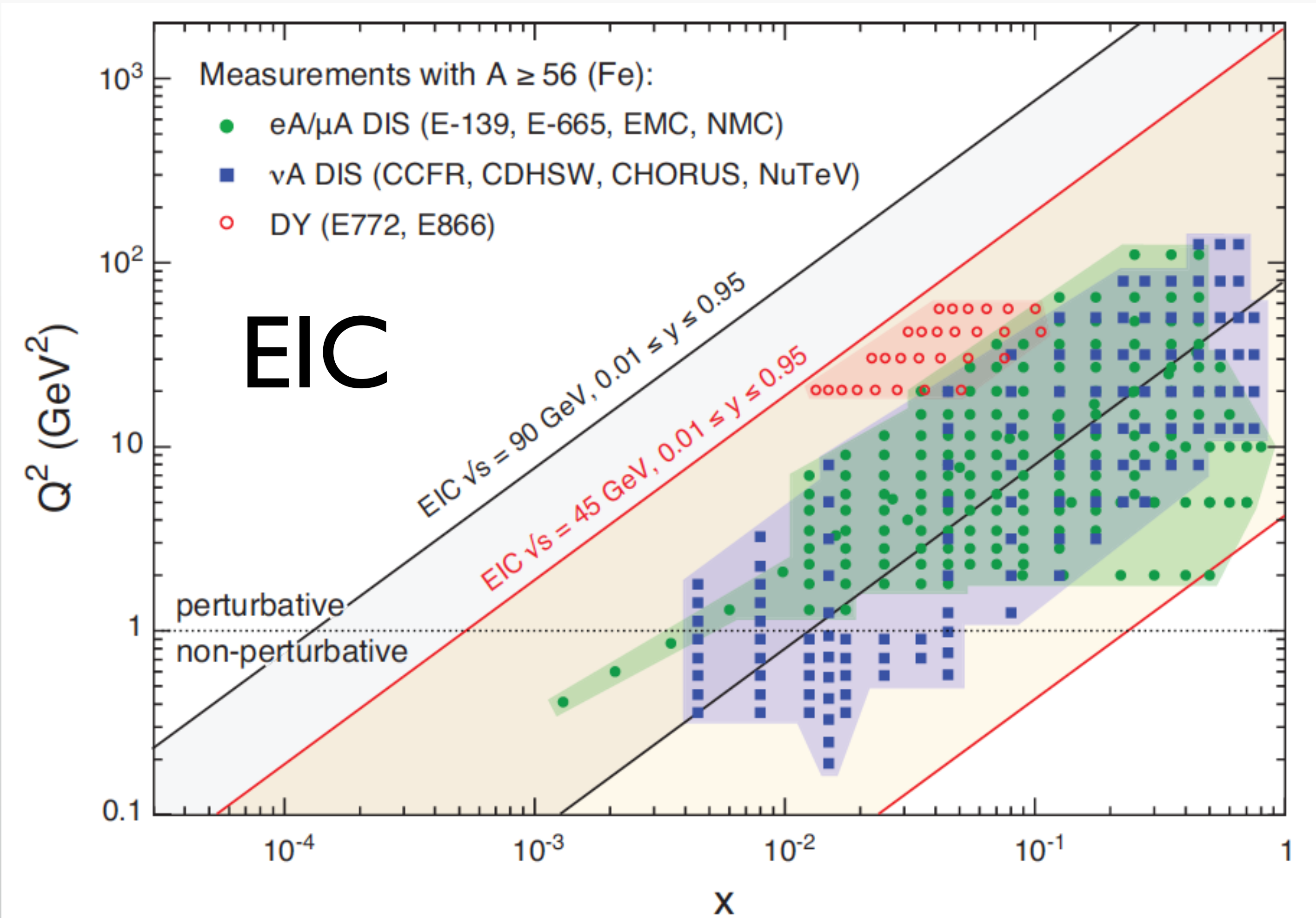
2. Present status.

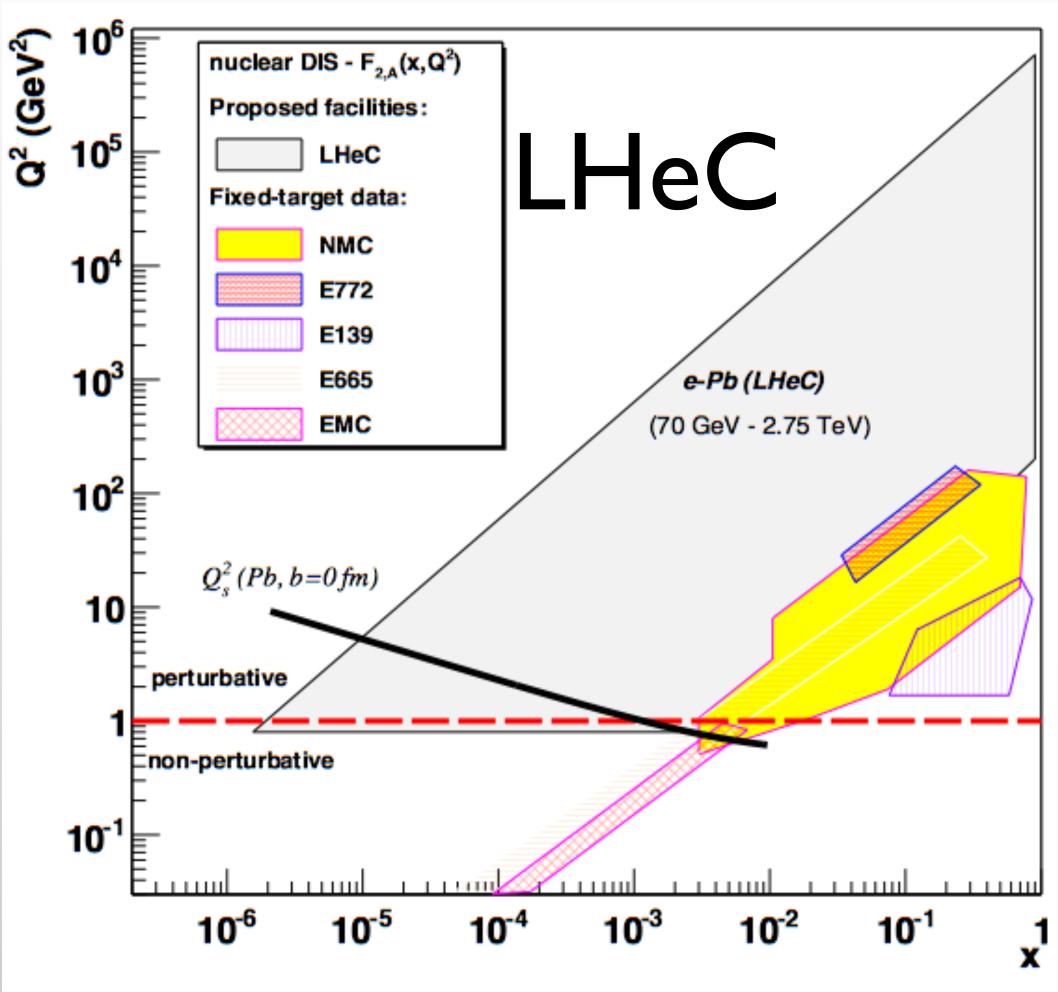
3. Impact of LHC pPb data.

4. Electron-ion colliders:
   - ➜ Framework.
   - ➜ The EIC.
   - ➜ The LHeC/FCC-he.
   - ➜ Deuteron.

5. Conclusions.

Kinematics:





- Advantages of DIS:

➜ cleaner experimental setup e.g. fully constrained kinematics;

➜ firmer theoretical grounds.

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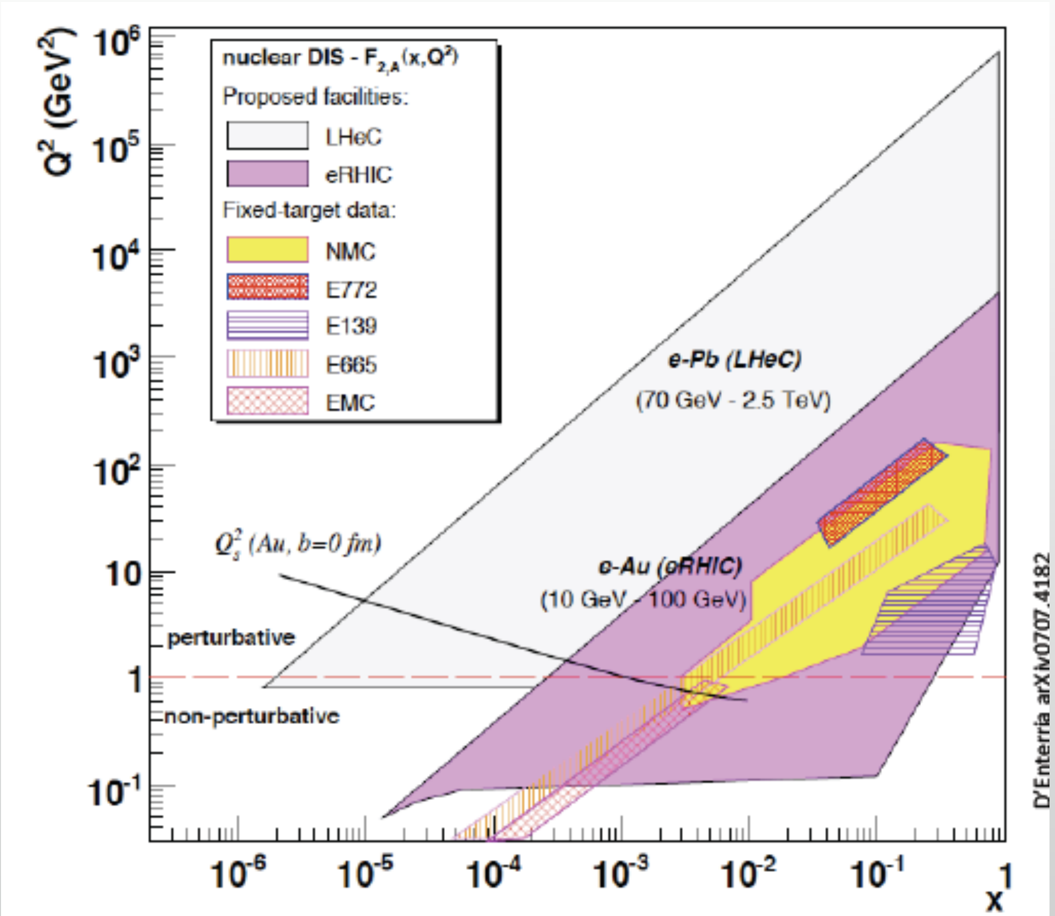

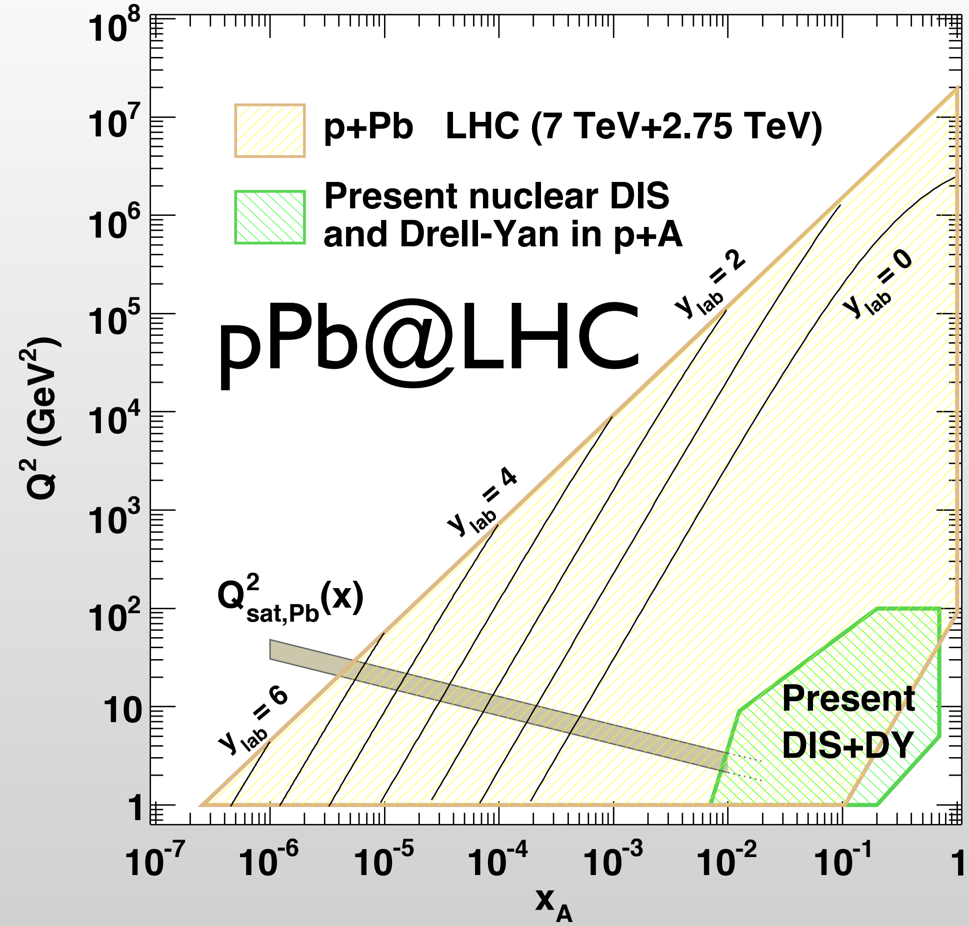

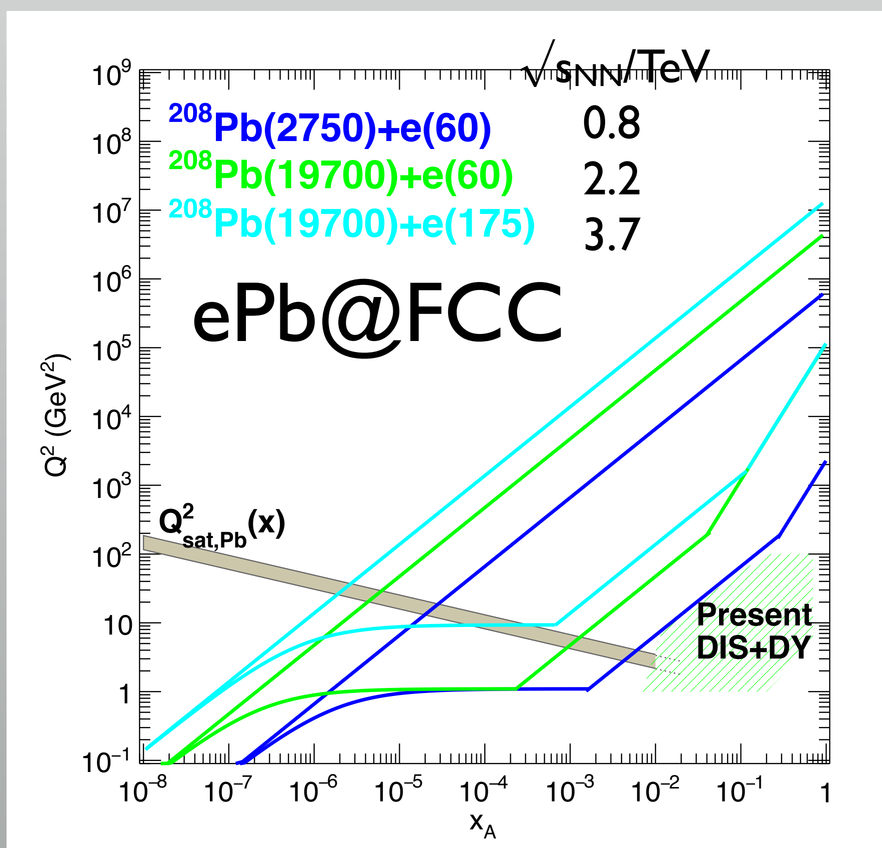

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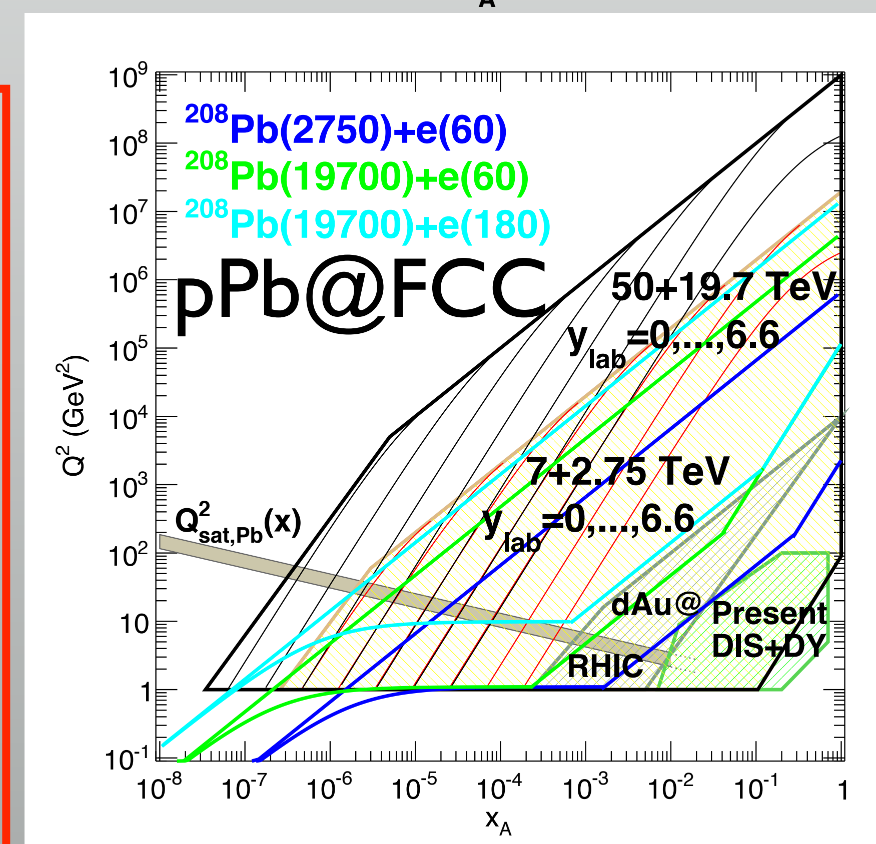
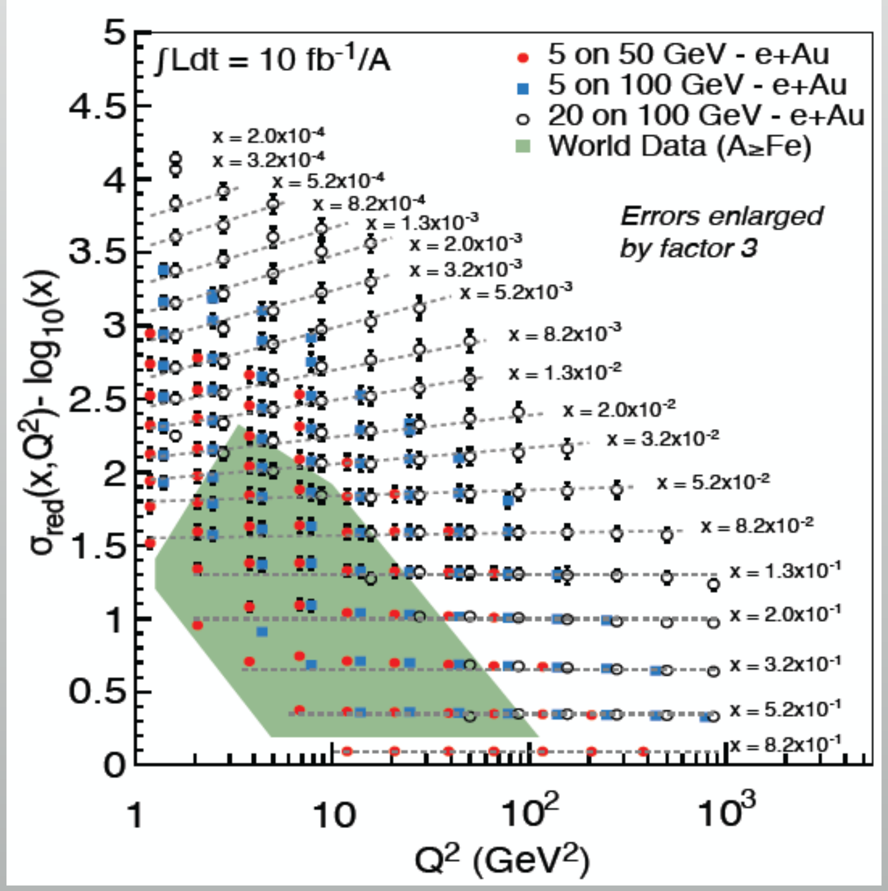
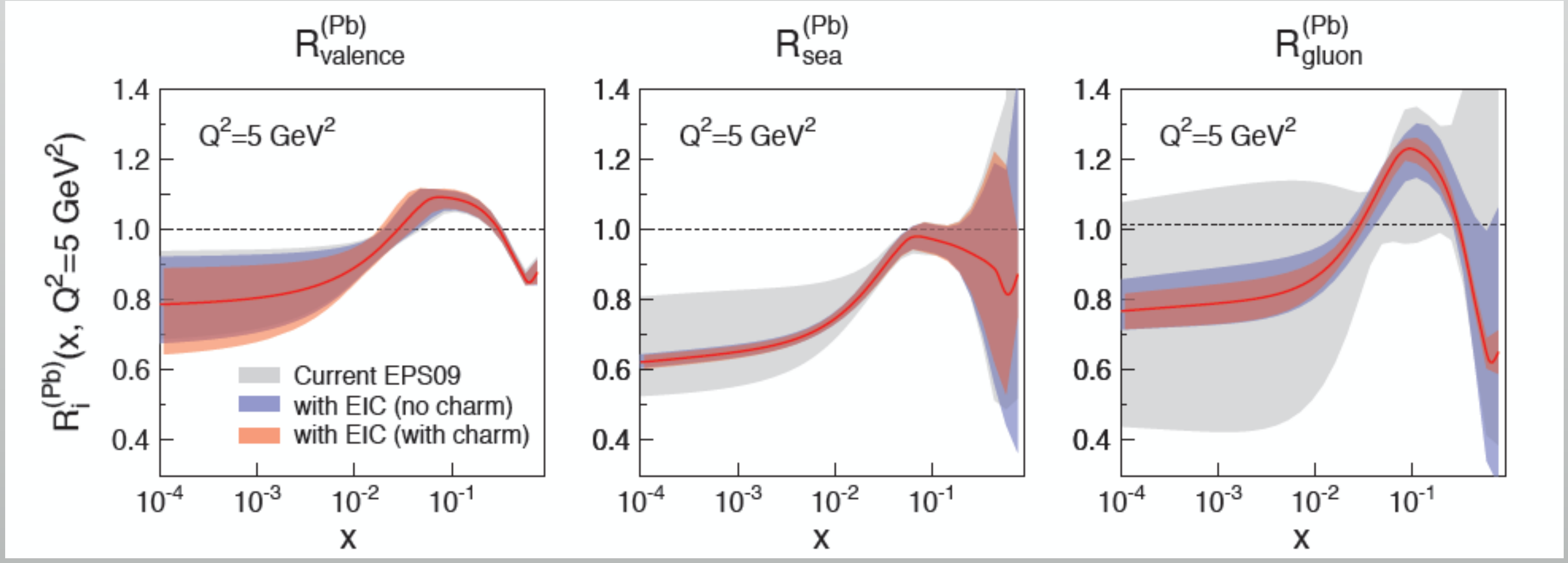


Parametrisation bias:

- Sensitivity to the mathematical form of the initial conditions is a well-known issue in proton PDFs: NNPDF, PDF4LHC recommendation of comparing different sets, HERAPDF2.0 studies, …
- In our case: determination of nPDFs beyond (pseudo)data…





EIC example

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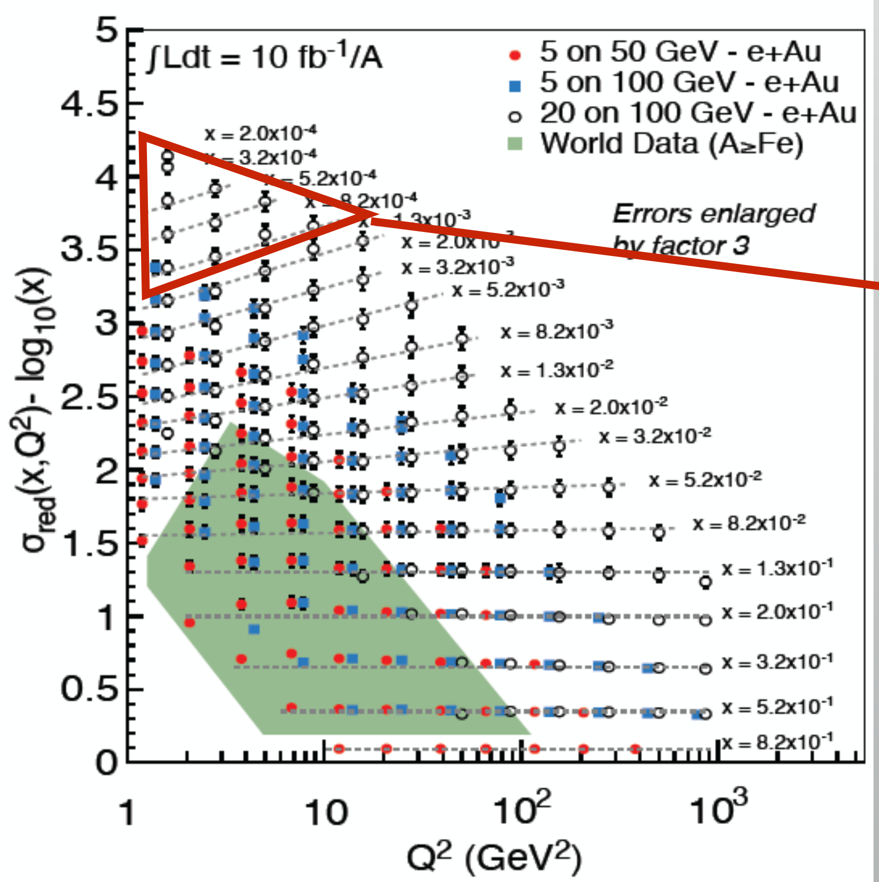
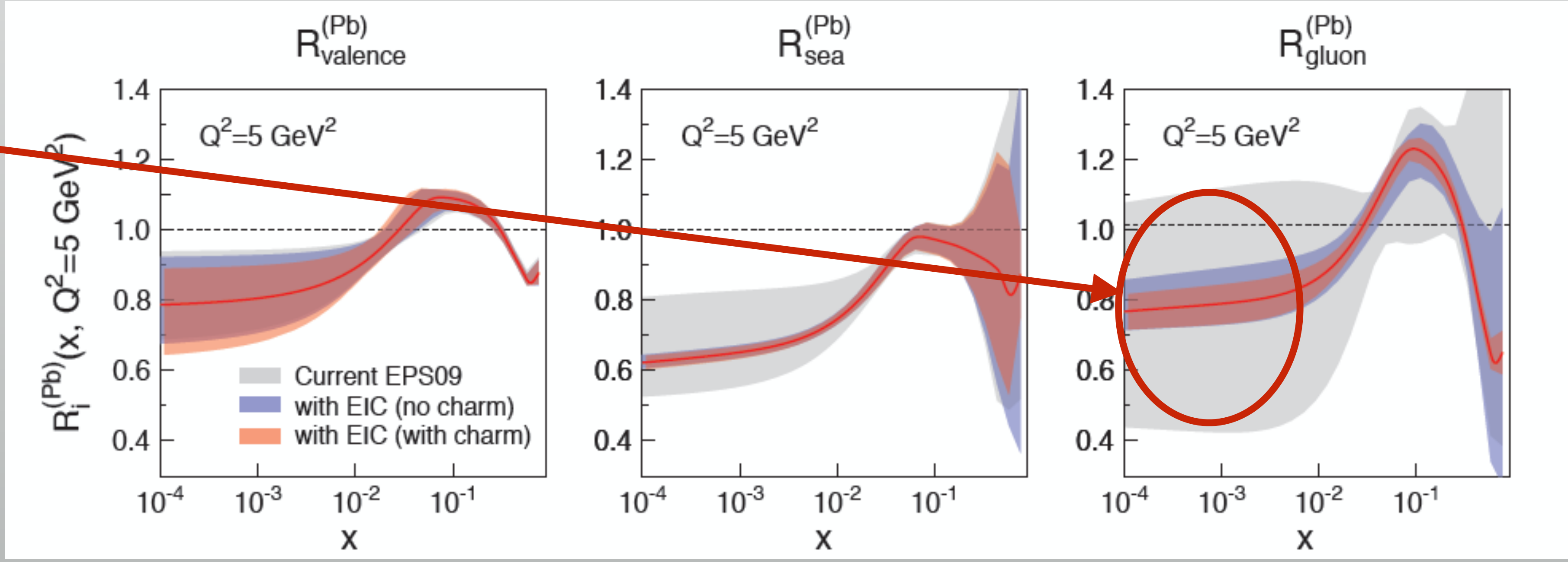


How?: mainly dictated by the shape of ICs



EIC example

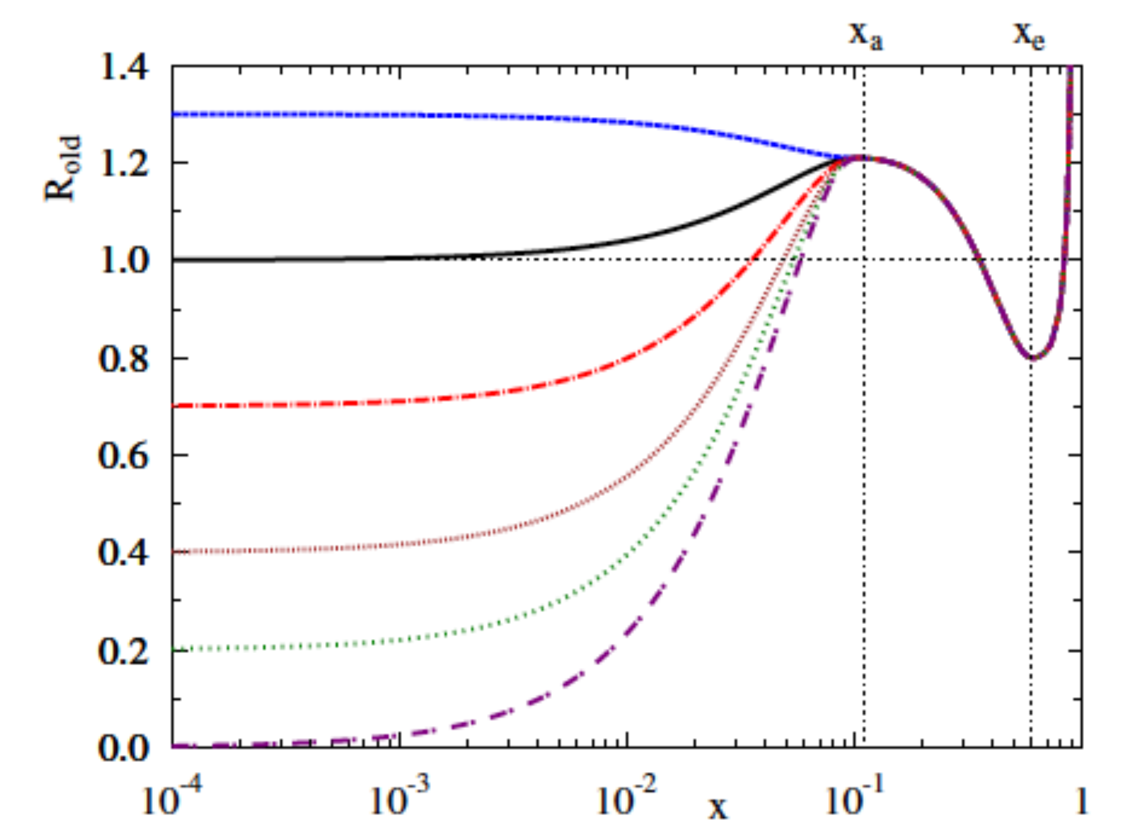
$$\frac{\partial R^A_{F_2}(x,Q^2)}{\partial \log Q^2} \approx \frac{10\alpha_s}{27\pi} \frac{xg(2x,Q^2)}{\frac{1}{2}F_2^{\rm D}(x,Q^2)} \left\{ R^A_g(2x,Q^2) - R^A_{F_2}(x,Q^2) \right\}$$

hep-ph/0201256

Parametrisation bias:

- An idea to deal with it in the EPS09 framework:

$$R_{\text{old}}(x) = \begin{cases} a_0 + (a_1 + a_2 x)\left(e^{-x} - e^{-x_a}\right) & x \le x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1 - x)^{-\beta} & x_e \le x \le 1, \end{cases}$$



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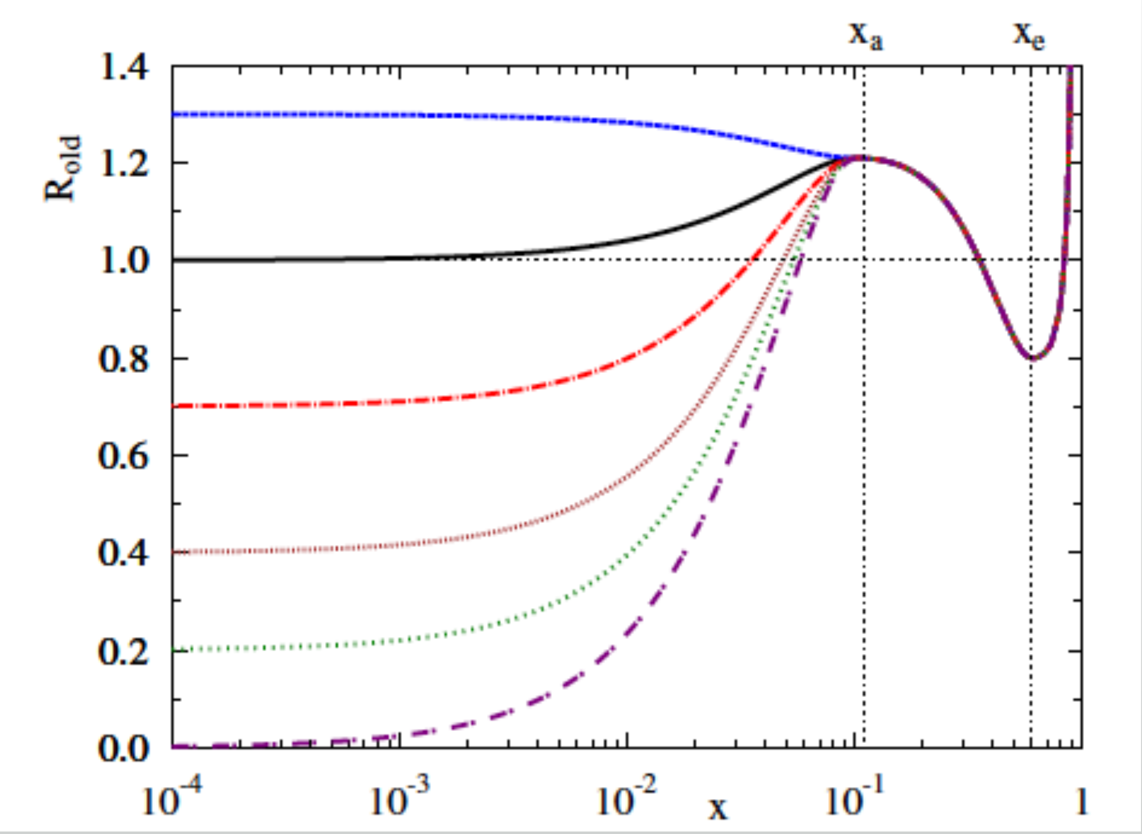
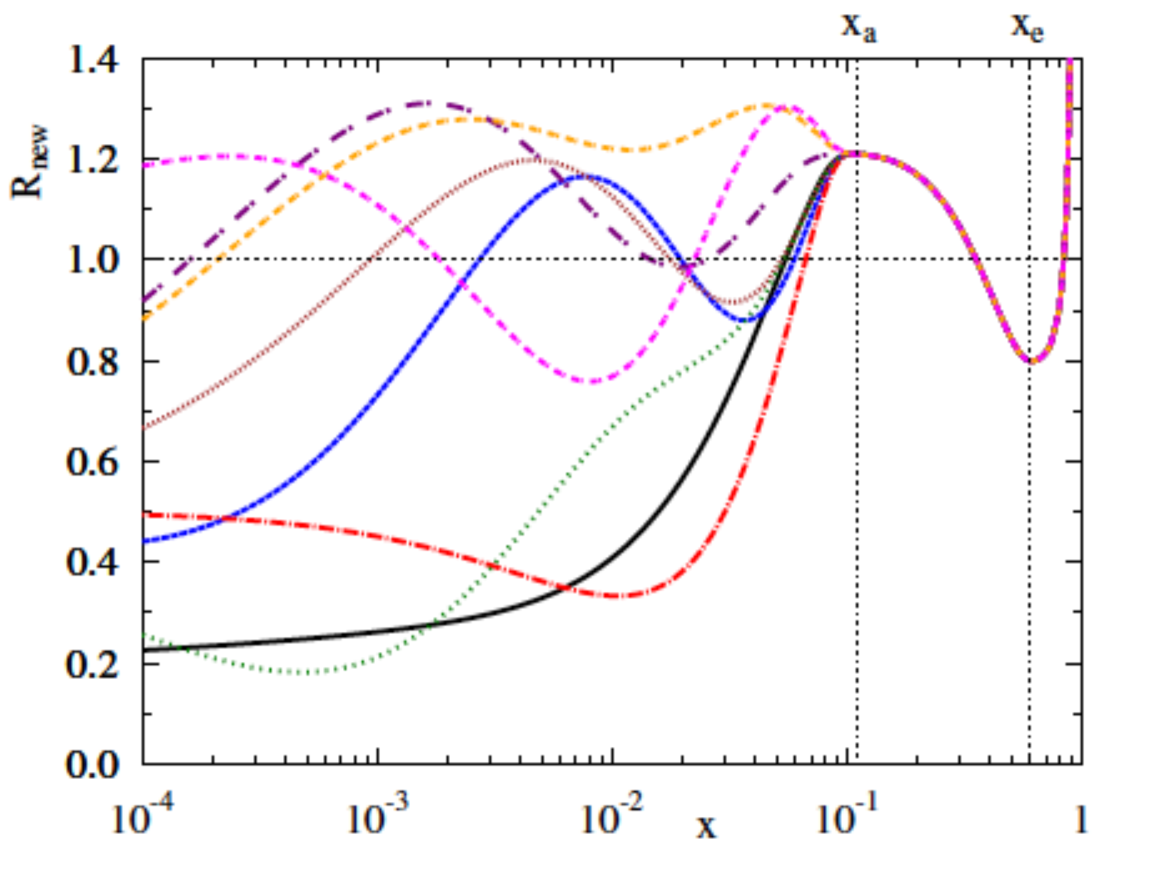
3 for LHeC

$$R(x \le x_a) = a_0 + a_1 (x - x_a)^2 + x(x_a - x)\left[\sum_{k=1}^{4} a_{k+2} \log\left(\frac{x}{x_a}\right)^k\right]$$

- 15 (orig.) → 19 (new) parameters.



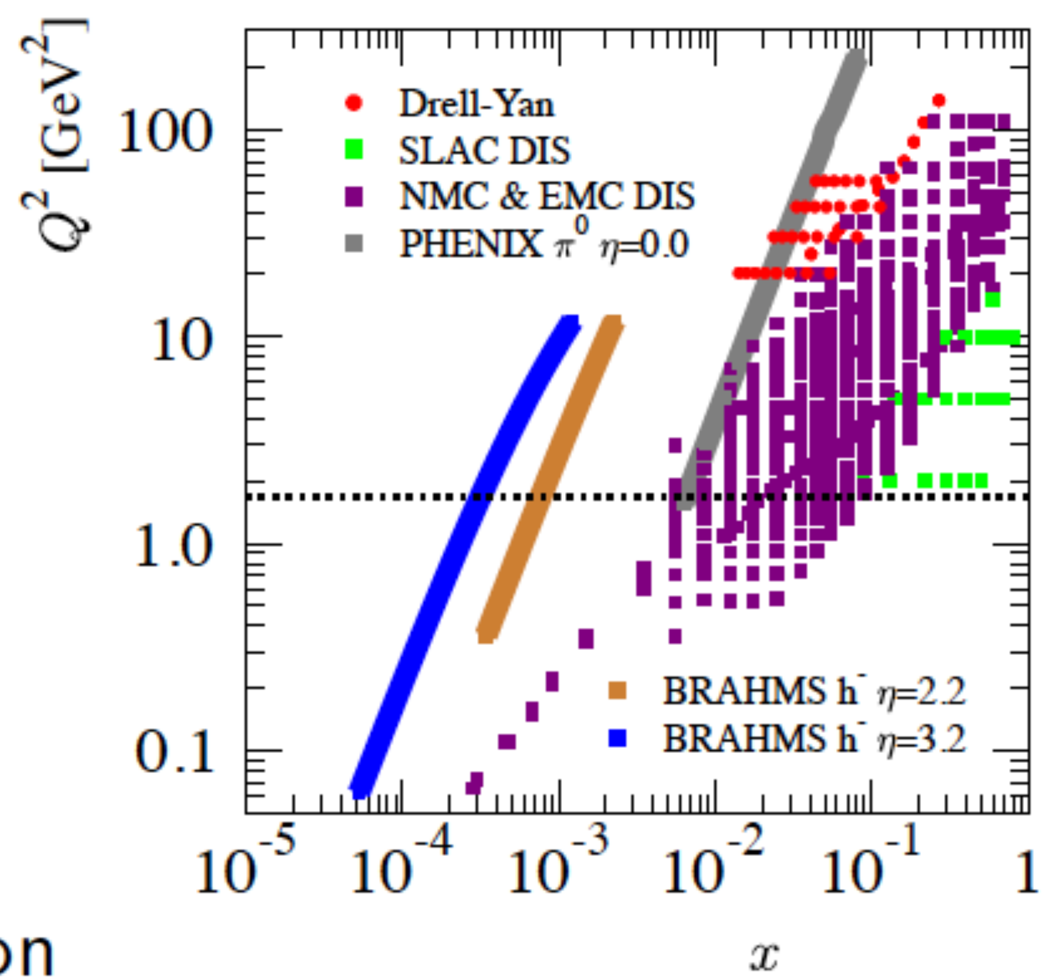


New fit framework:

Paukkunen

- Include the same data (DIS, Drell-Yan, inclusive π^0) as in EPS09 (no LHC data yet) plus LHeC (neutral current) pseudo data.
- CTEQ6.6 as baseline (doesn't really matter which one)
- Flavour-independent nuclear modifications at $Q_0 = 1.3\,\mathrm{GeV}$

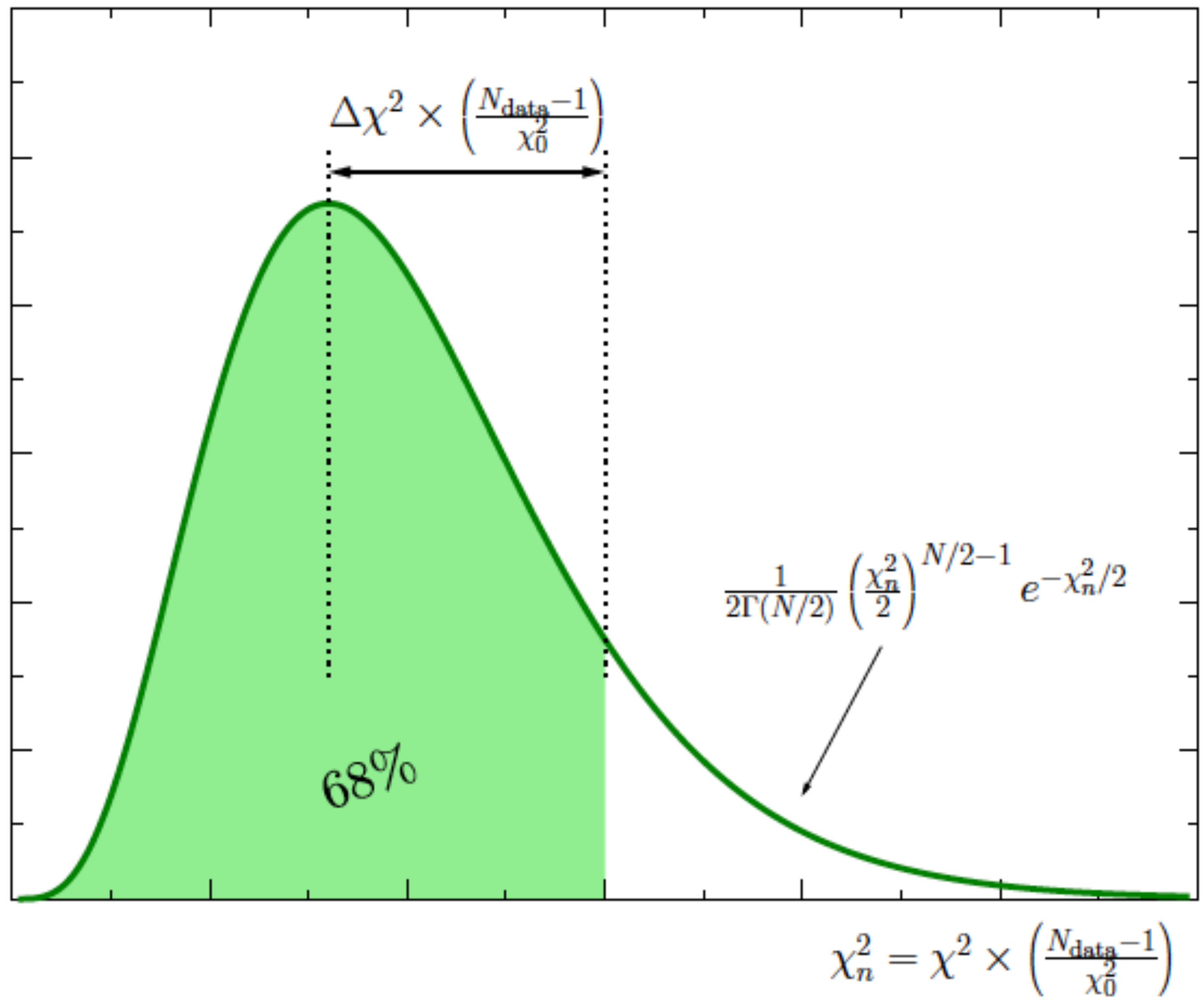
$R_\mathrm{V}(x, Q_0)$ for both valence quarks
$R_\mathrm{S}(x, Q_0)$ for light sea quarks
$R_\mathrm{G}(x, Q_0)$ for gluons



- Charged-current data will be added later on to study the flavour dependence
- Cross-sections at NLO in the SACOT heavy-quark scheme (as CTEQ6.6)
- Robust Levenberg-Marquardt minimization method

New fit framework: Paukkunen

Standard Hessian uncertainty analysis (a la CTEQ, MSTW,...) with $\Delta\chi^2$ determined from the expected behaviour of probability distribution for the global χ^2

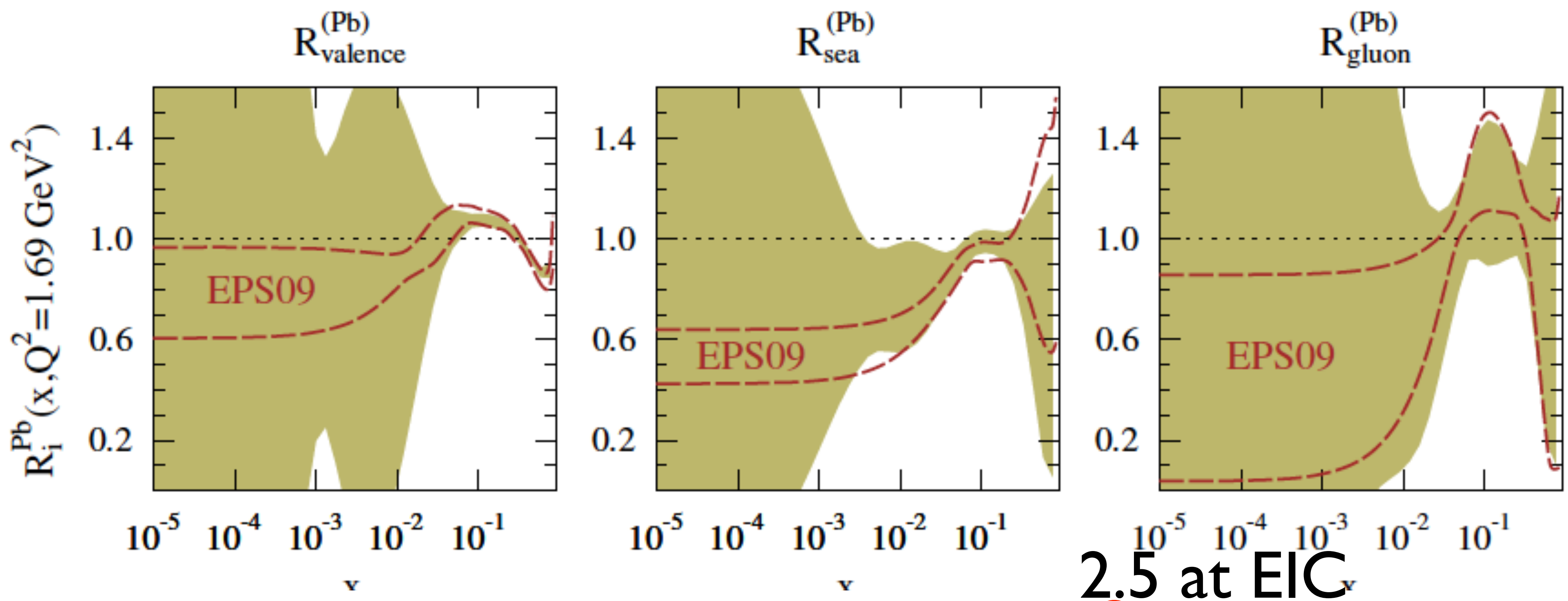


Gives $\Delta\chi^2 \approx 17$ (without or with the pseudodata)

New fit framework:

Paukkunen

The baseline fit using the new fit functions: no control over small x!



2.5 at EIC

The lower bound restricted here by $F_L(Q^2 = 2\,\mathrm{GeV}^2, x > 10^{-5}) > 0$

Maybe against "physical intuition" (small-x theory predicts shadowing, $R_i < 1$), but consistent with the data.

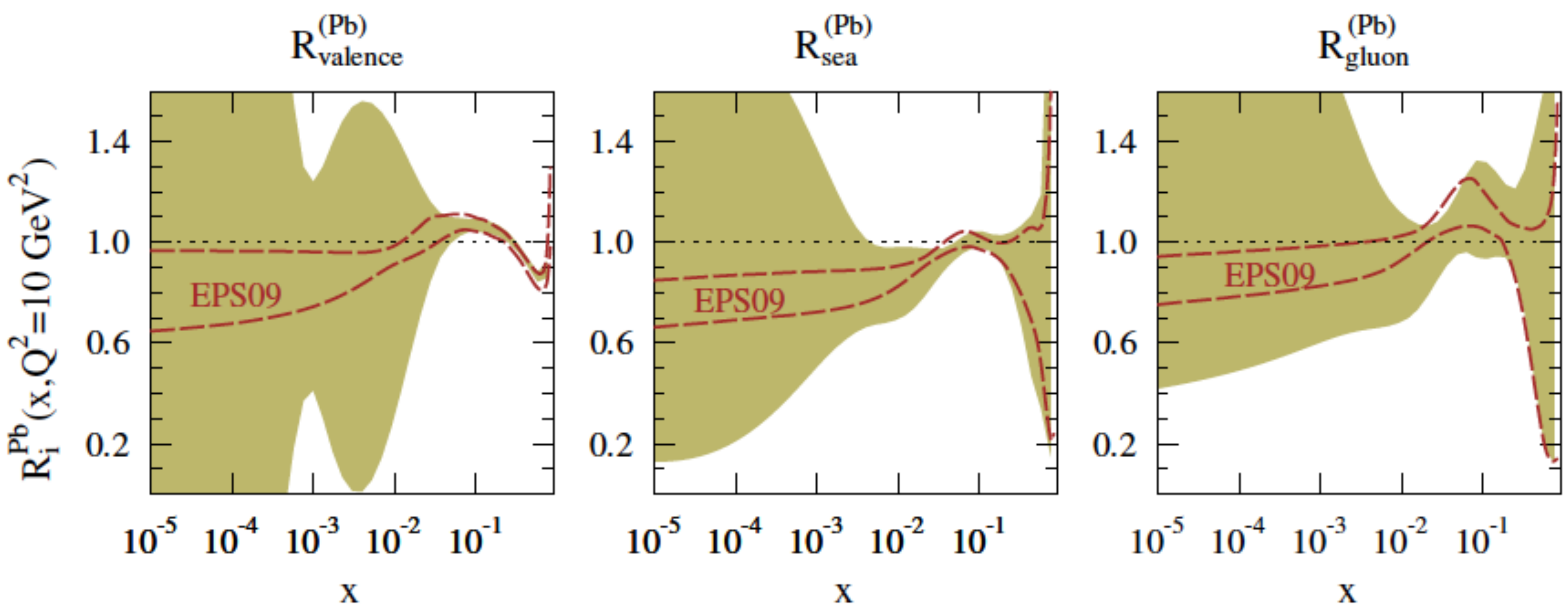
E.g. in EPS09, small-x shadowing was essentially built in

New fit framework:

Paukkunen

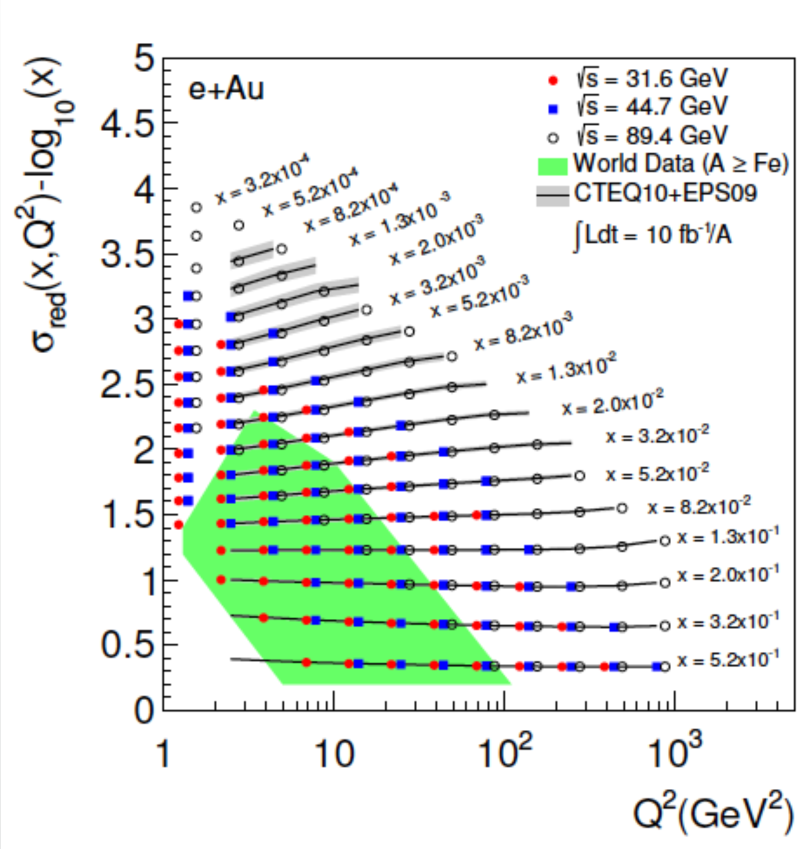
The baseline fit using the new fit functions: no control over small x!

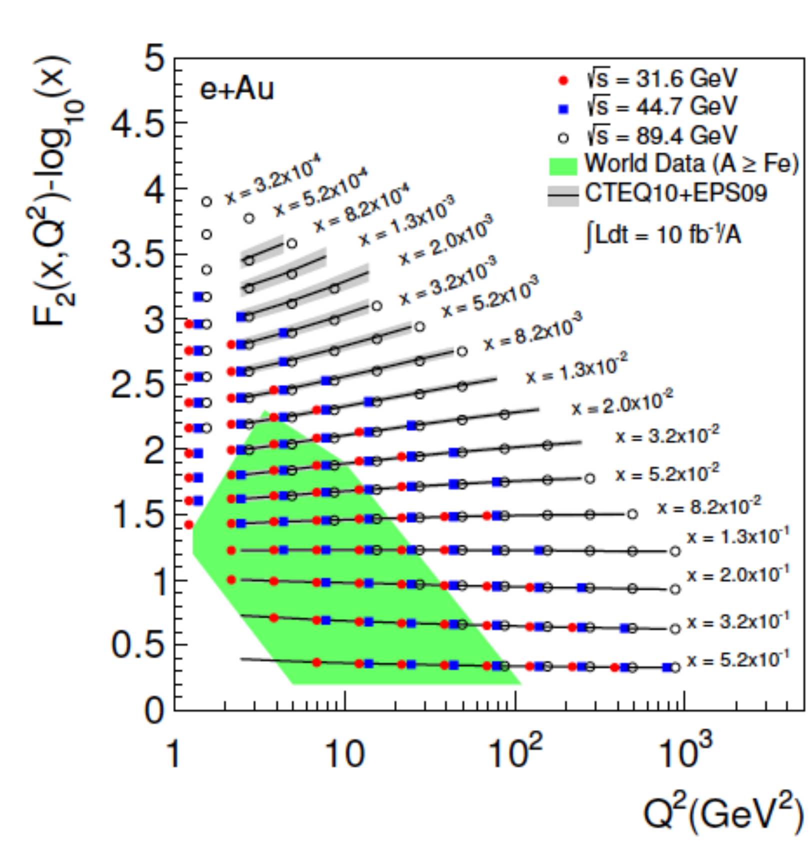
The Q^2 dependence partly smooths out the differences in gluons

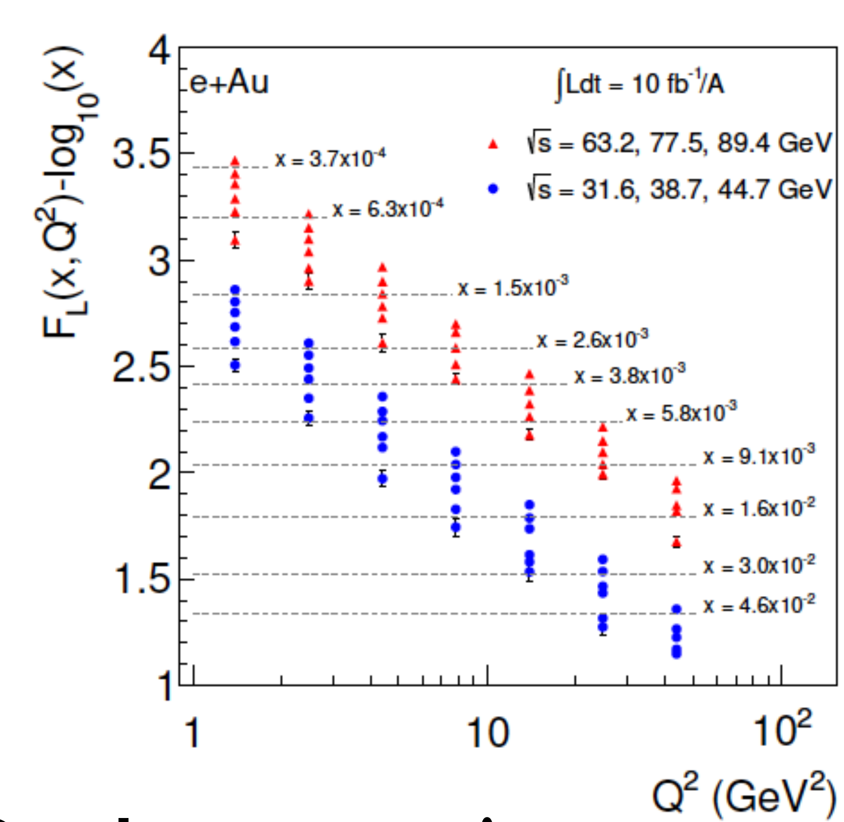


EIC: pseudodata

Inclusive

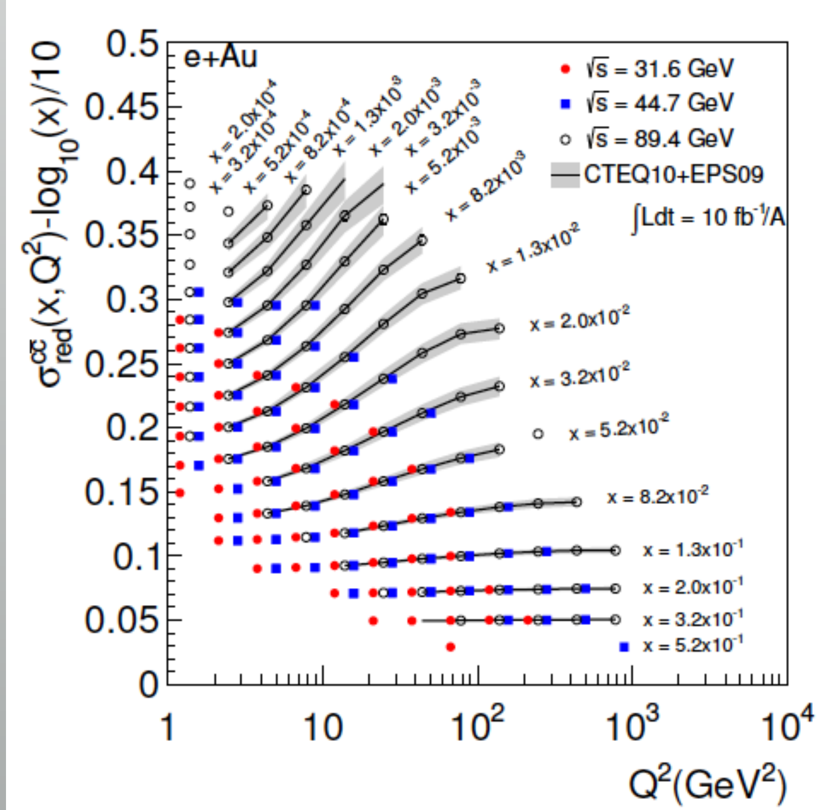


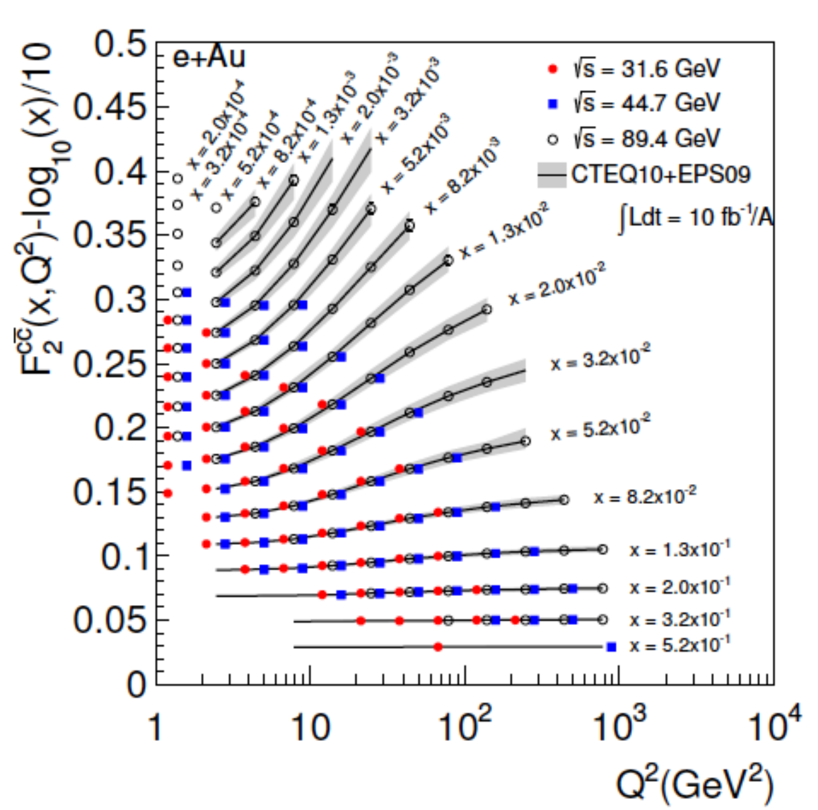


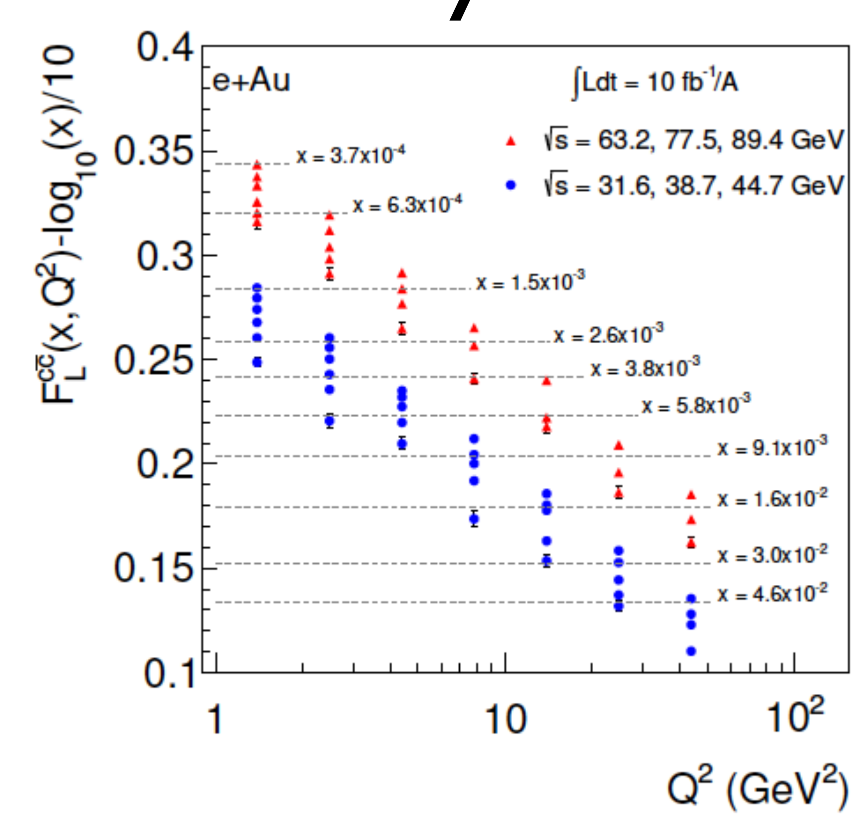


Preliminary!

Charm







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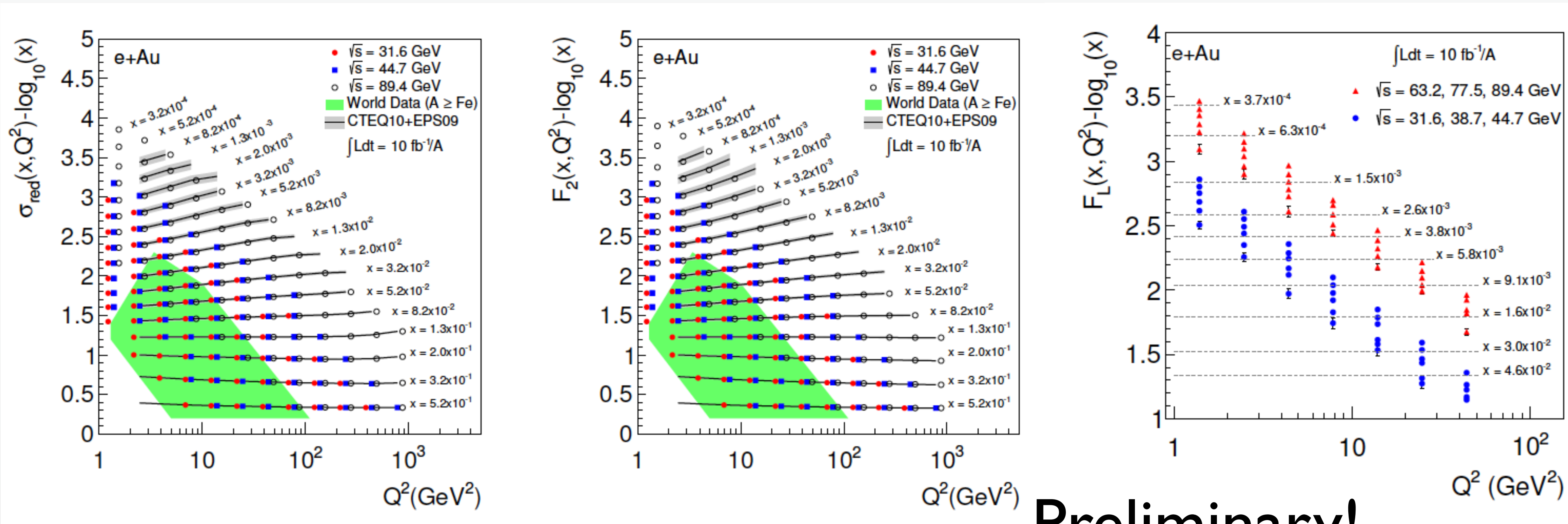

Preliminary!

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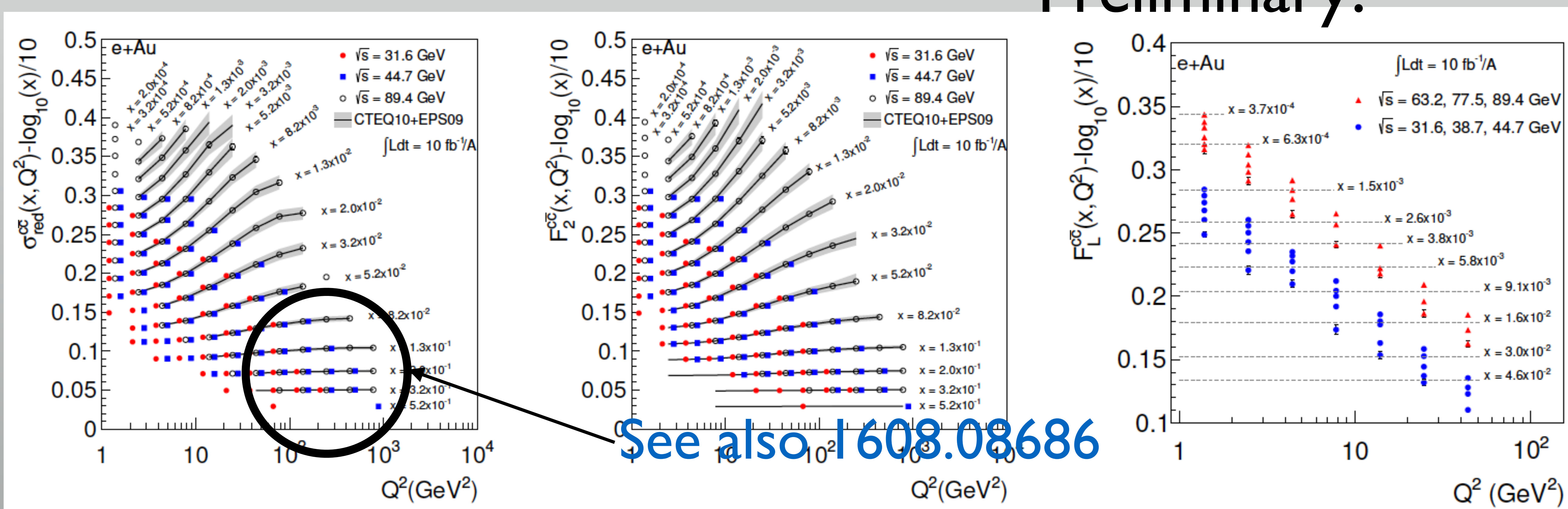
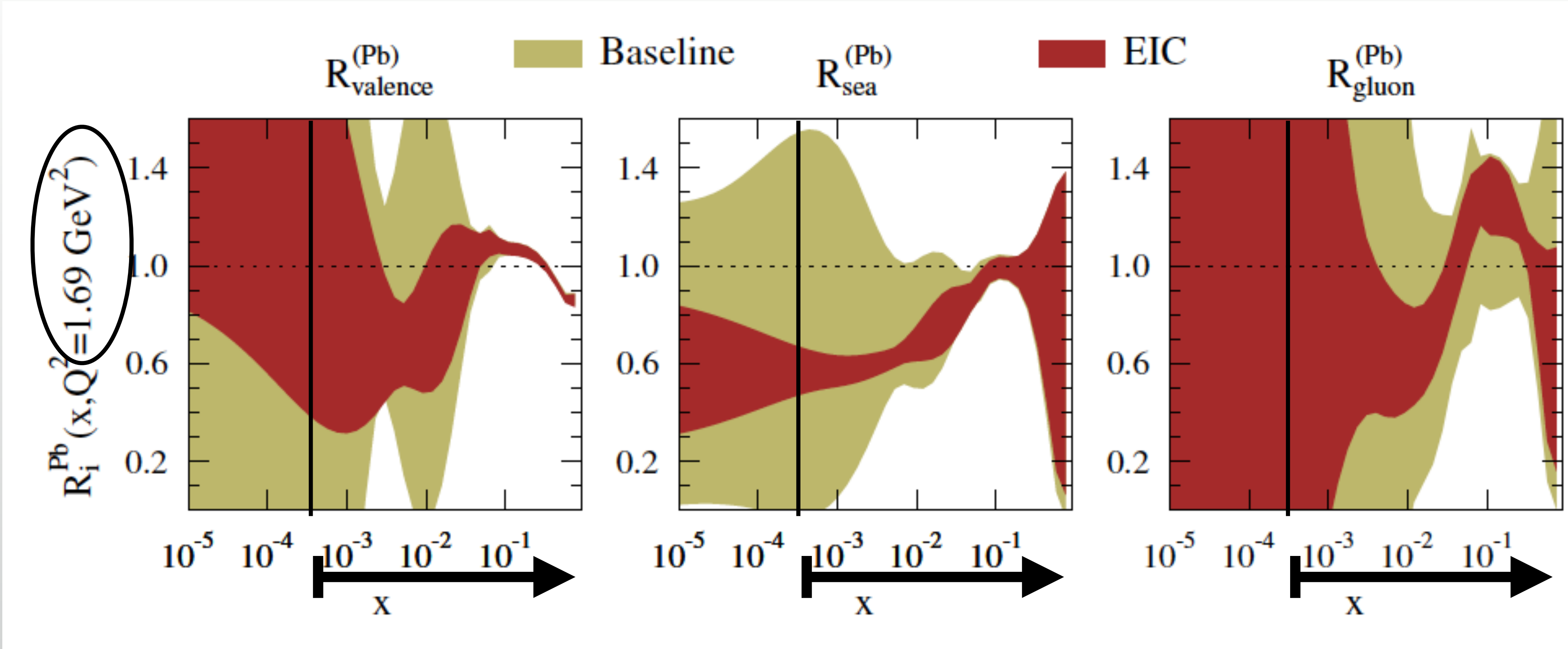


See also 1608.08686

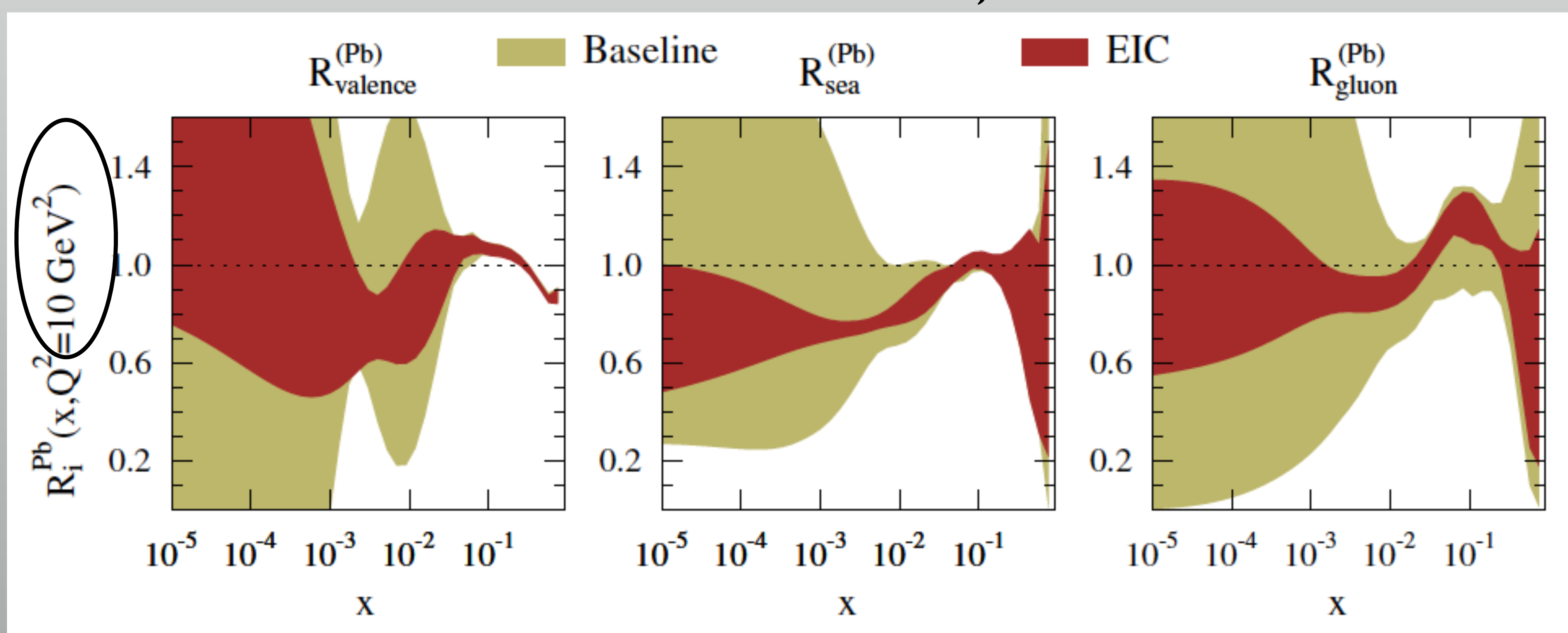
EIC: nPDFs

Preliminary!



- Substantial reduction of uncertainties, moderate effect of charm.

Preliminary!



EIC: nPDFs

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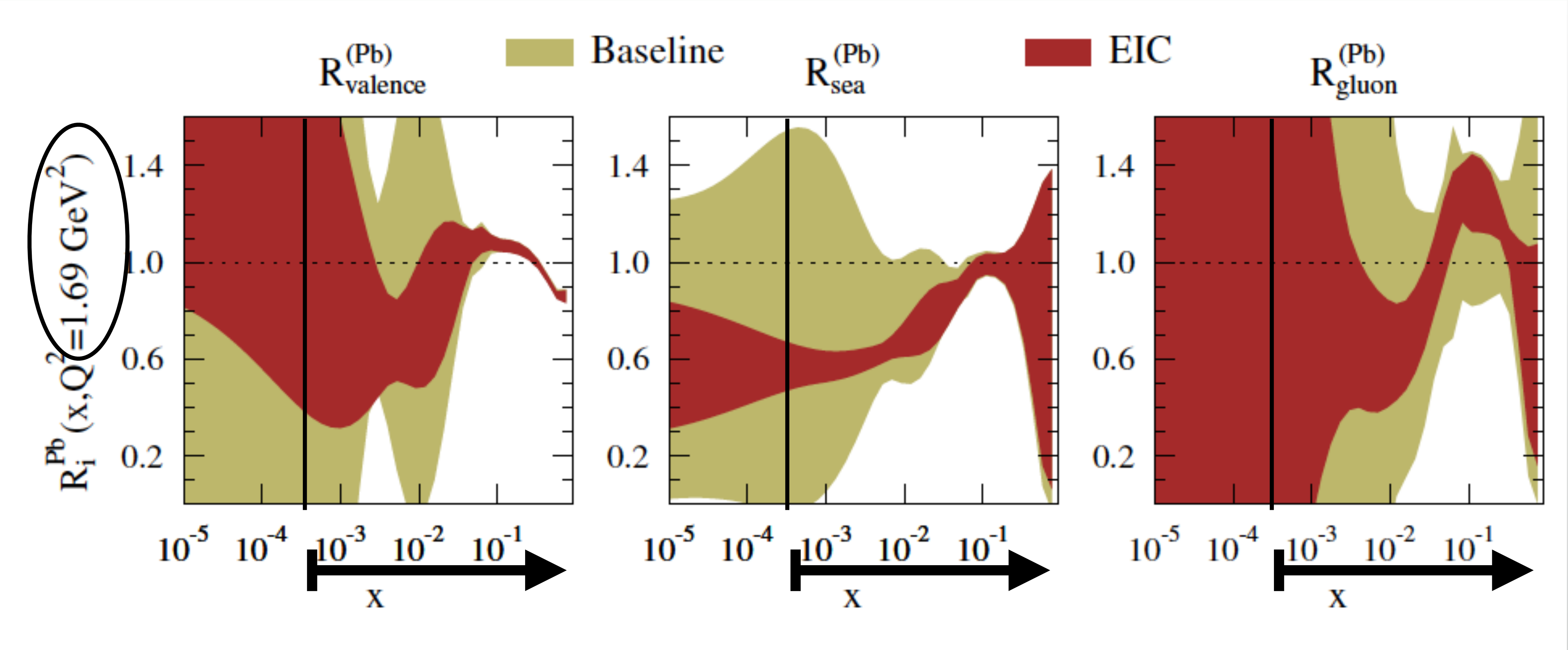

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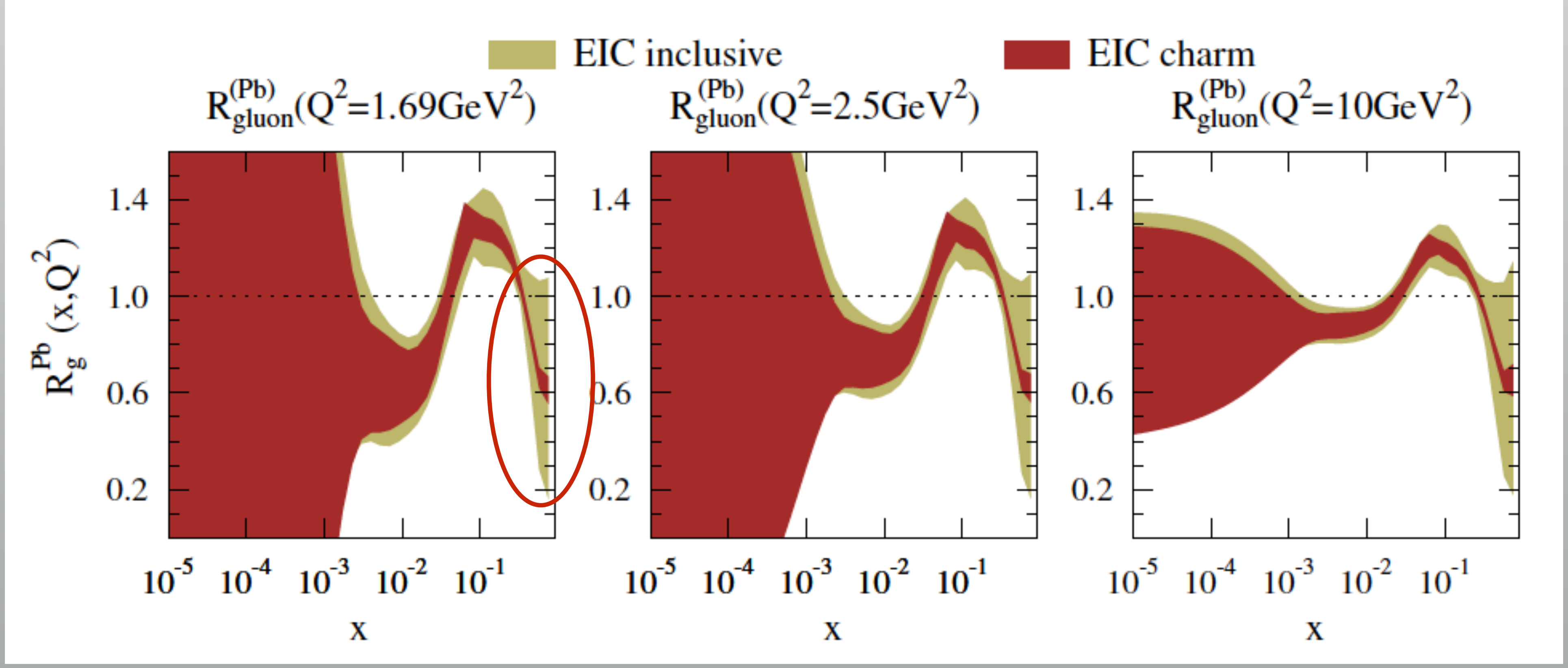
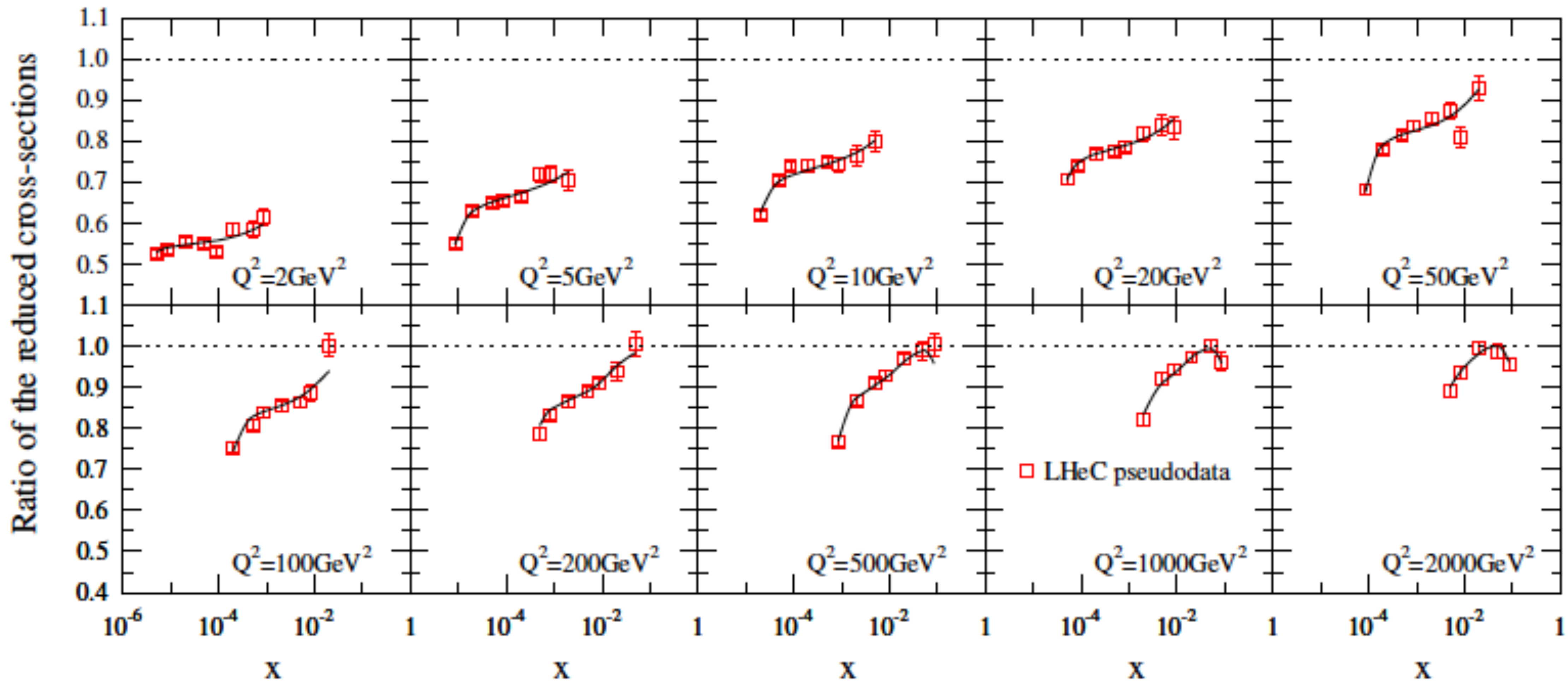


N. Armesto, 14.11.2016 - nPDFs at an EIC: 4. Electron-ion colliders.

LHeC: pseudodata

- Simulation: NC(+CC+c,b not yet used) with systematic uncertainties from a complete simulation.



Checked that $\chi^2/N_{\rm data}$ to the underlying truth (=EPS09 ;)) fluctuates about unity depending on the random numbers that got chosen

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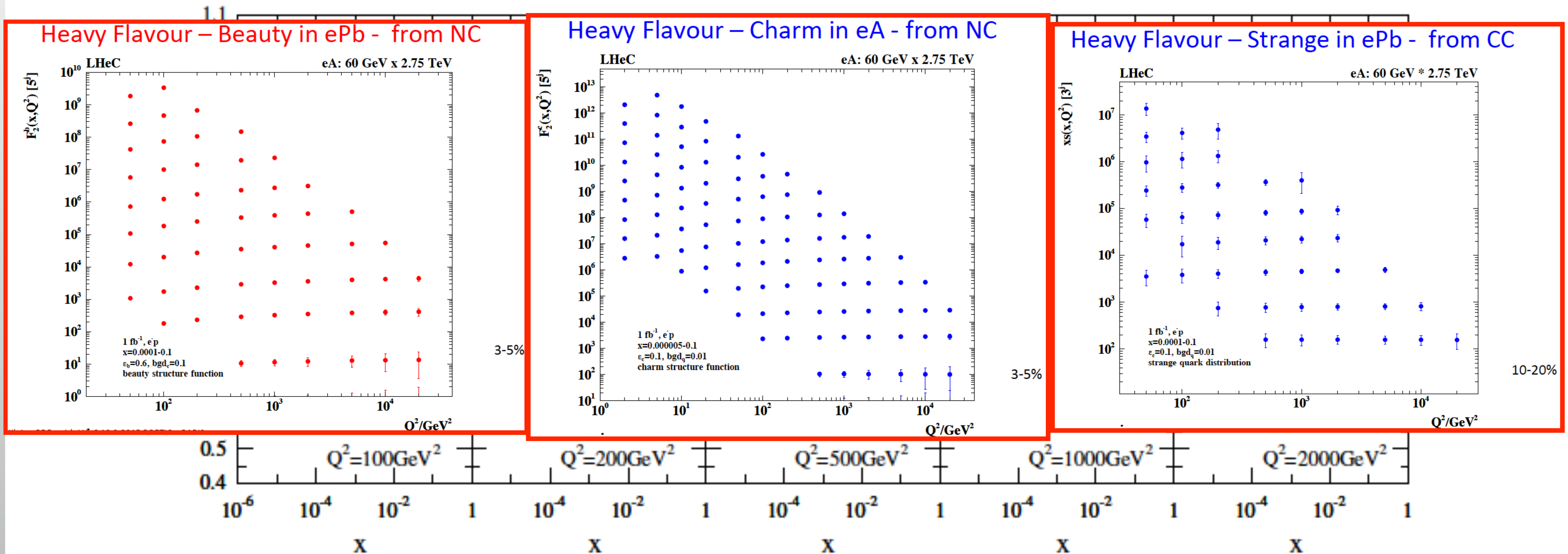

M. Klein at POETIC6

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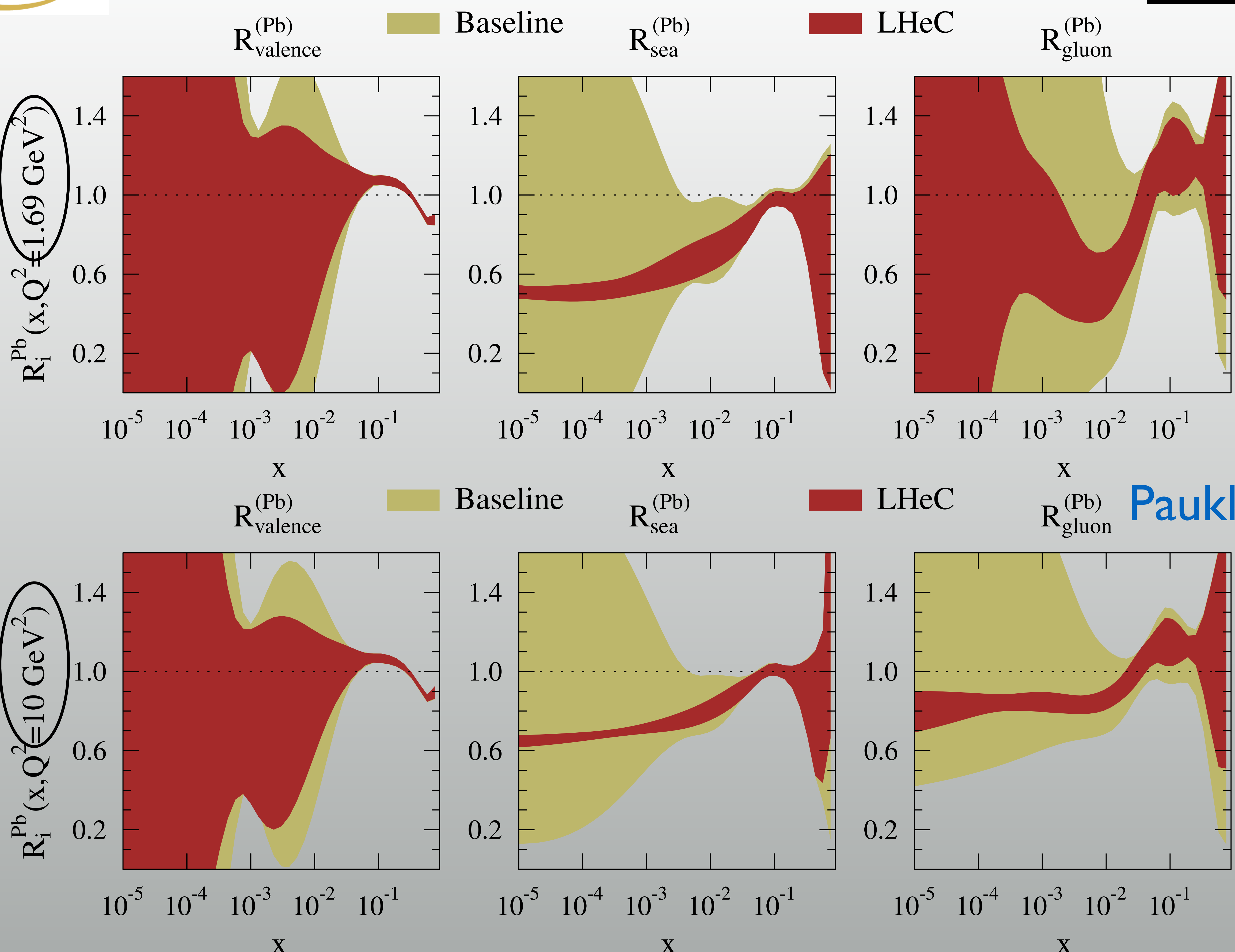
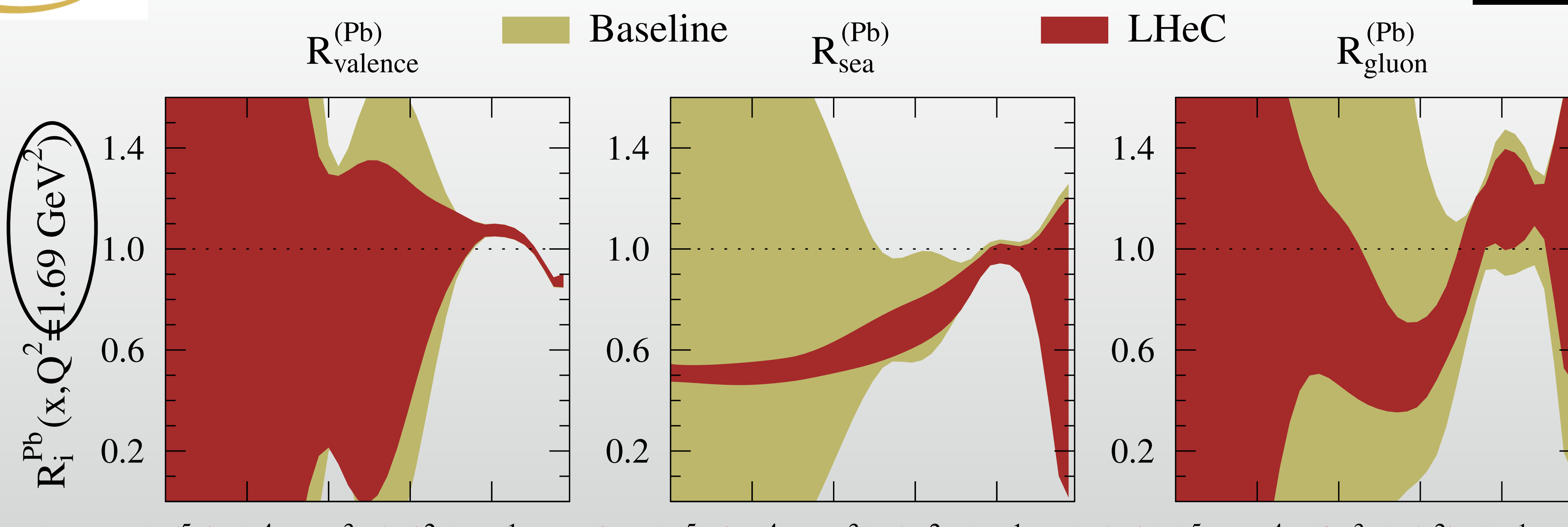
LHeC: nPDFs

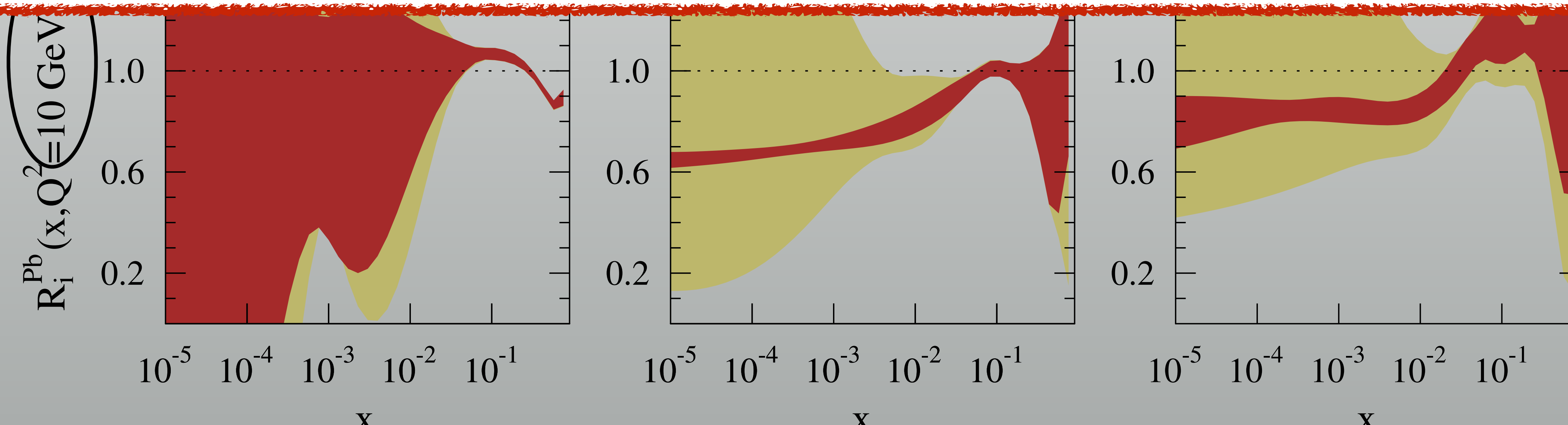


Paukkunen

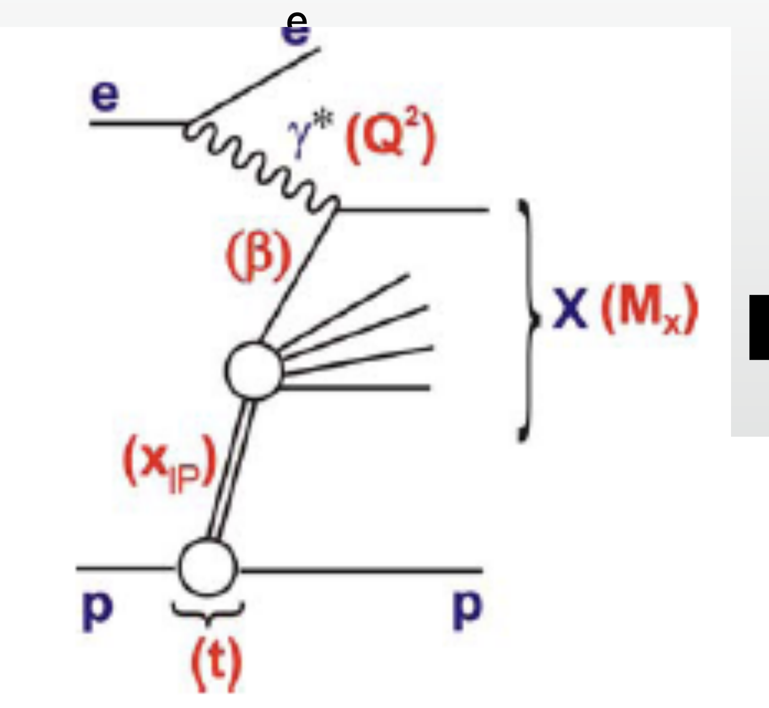
LHeC: nPDFs

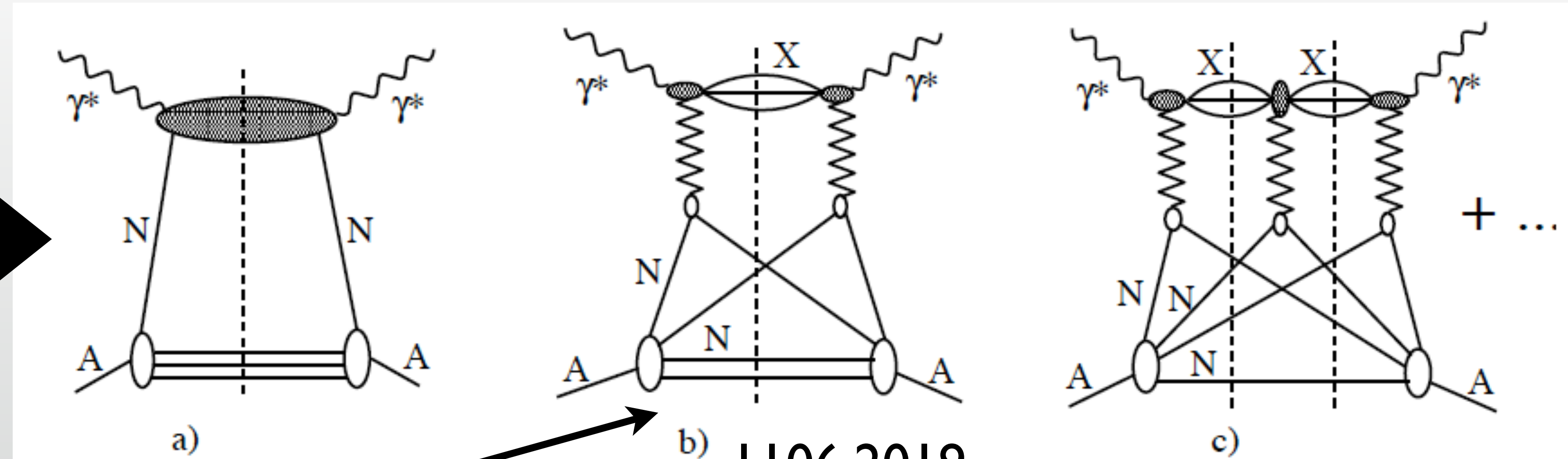


- Substantial reduction of uncertainties.
- EICs provide the nPDFs with the precision required for the heavy-ion programmes at RHIC, LHC and future colliders.



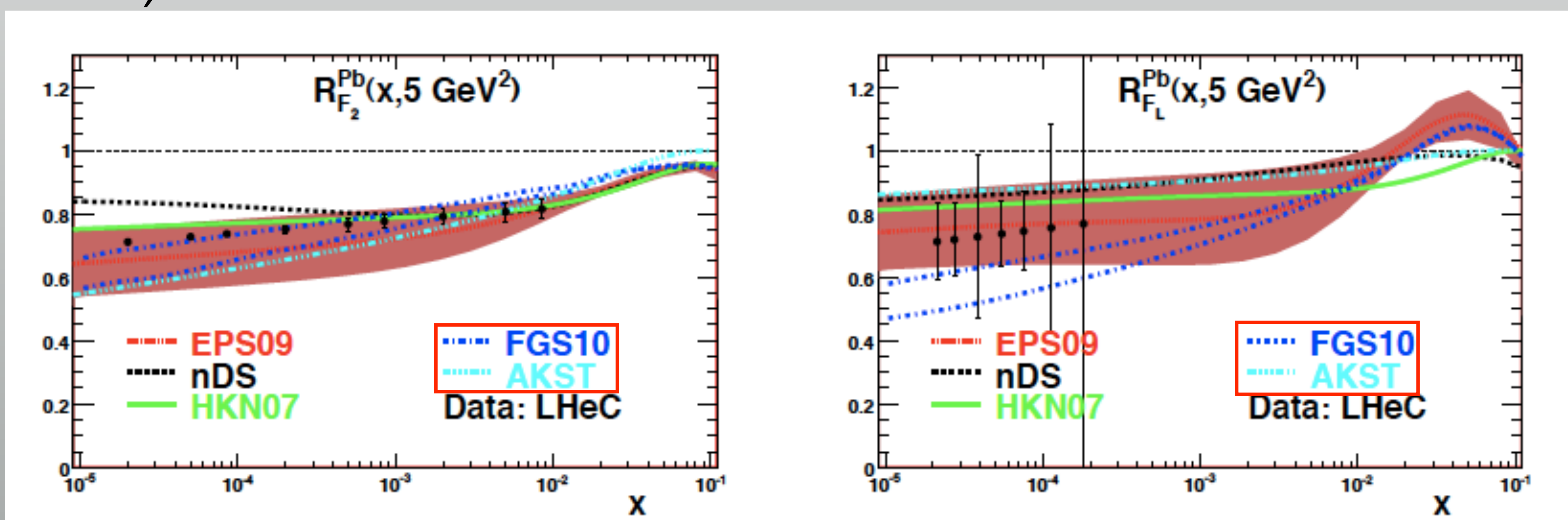
Deuteron:





1106.2019

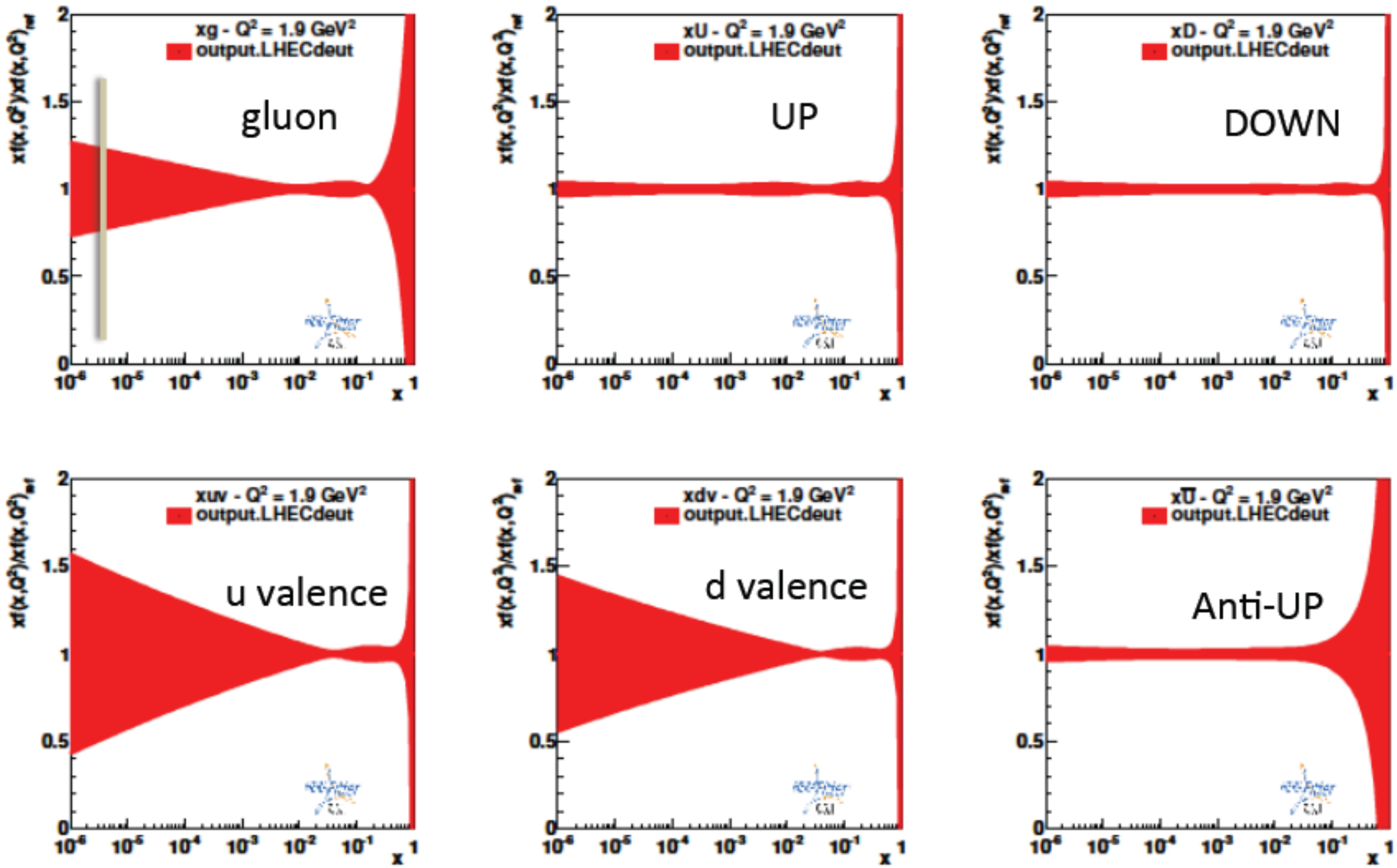
- Diffraction is linked to nuclear shadowing through basic QFT (Gribov): eD to test and set the 'benchmark' for new effects.



Deuteron:

Standalone eD analysis – the forgotten neutron..

3.5 TeV x 60 GeV, e-, P=-0.8, 1fb-1 Neutral and Charged Current, exp uncertainties

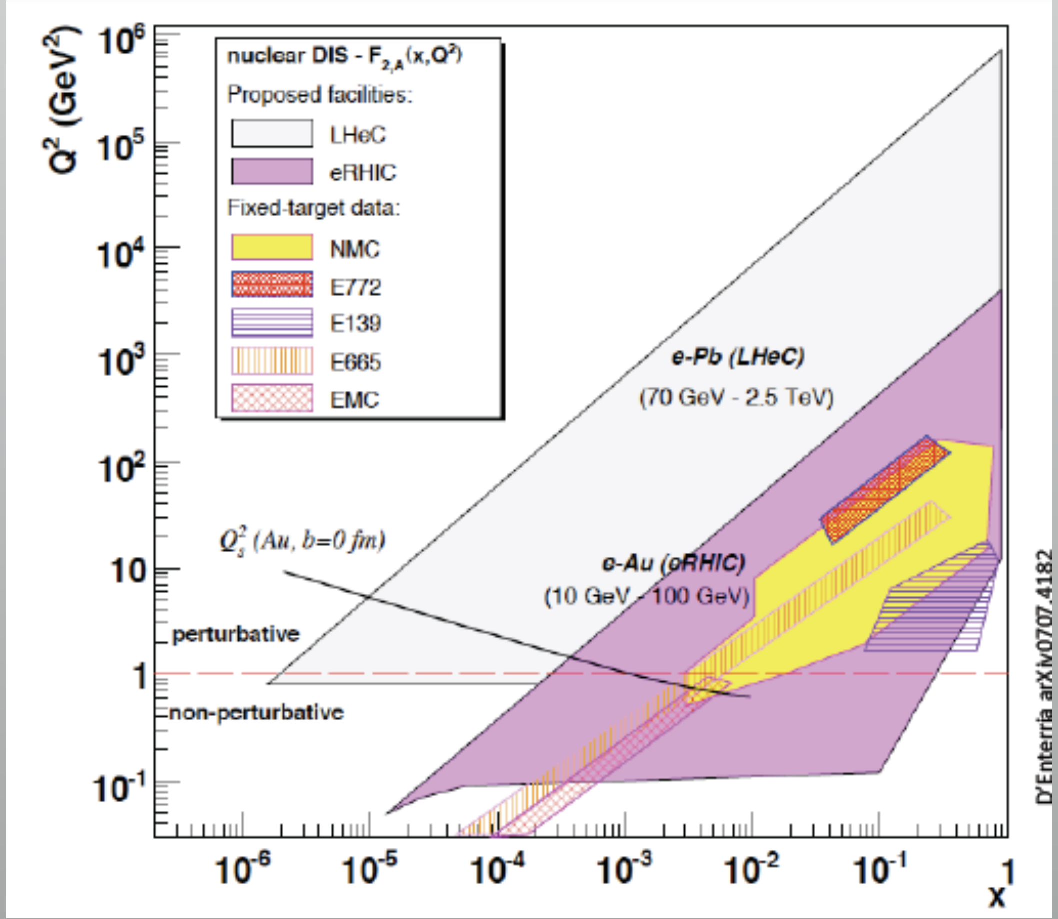


Future fit of jointly ep and eD data will lead to precise unfolding of u-d

Max Klein nPDFs with LHeC 10.9.2015 POETIC a PARIS

Conclusions:

- nPDFs are poorly known considering the needs of of the heavy-ion programmes.
- Hadron colliders (RHIC, LHC) will provide information, particularly at small x, but DIS is needed:
  - ➜ Factorisation to be checked with PDFs extracted from several reactions.
  - ➜ Effects beyond fixed order pQCD (resummation, saturation) can be hidden in the PDFs: need of several observables.
- eA colliders will provide a substantial improvement in the full kinematical domain, with complete flavour decomposition possible.



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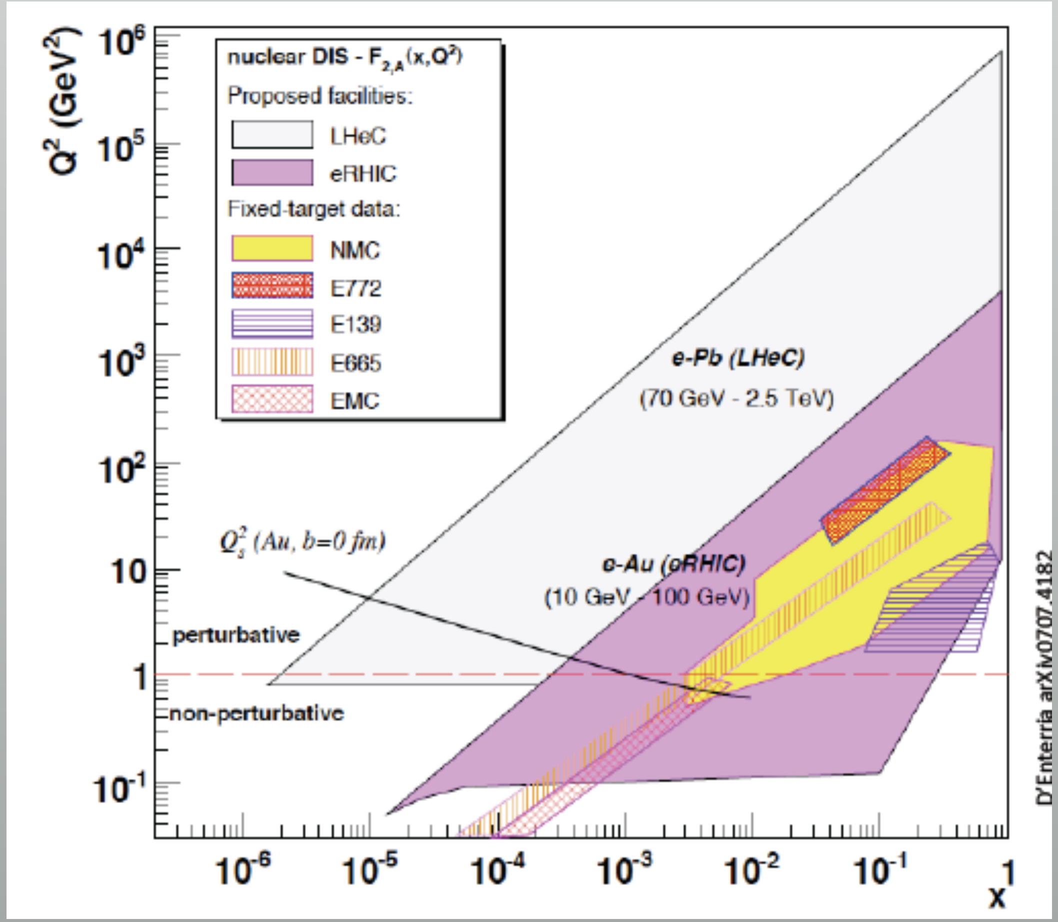
• To do:

➜ Include NC, CC, s,c,b,t, at all x.

➜ Obtain PDFs for a single nucleus in a single experiment, $\Delta\chi^2=1$.

➜ Analyse the tensions between different observables if pseudodata containing e.g. saturation are included.

➜ Radiative corrections.



Conclusions:

Many thanks to:

➜ *Elke Aschenauer and Thomas Ullrich for information and material about the most recent EIC fits.*

➜ *José Manuel Penín for providing projection plots for HL-LHC.*

➜ *John Jowett, Max and Uta Klein, Paul Newman, Hannu Paukkunen, Voica Radescu, Anna Stasto and Pía Zurita for many things.*

➜ *The organisers for their invitation to provide this talk.*

➜ *You all for your attention.*

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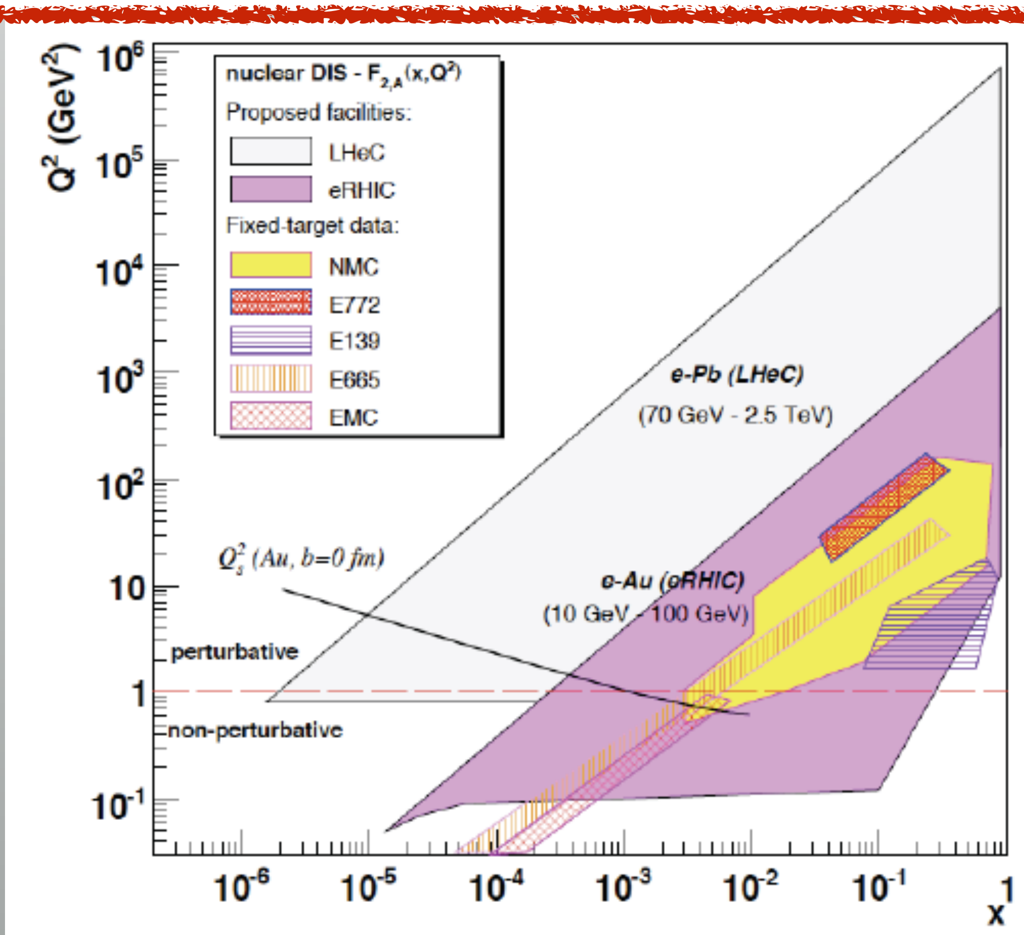
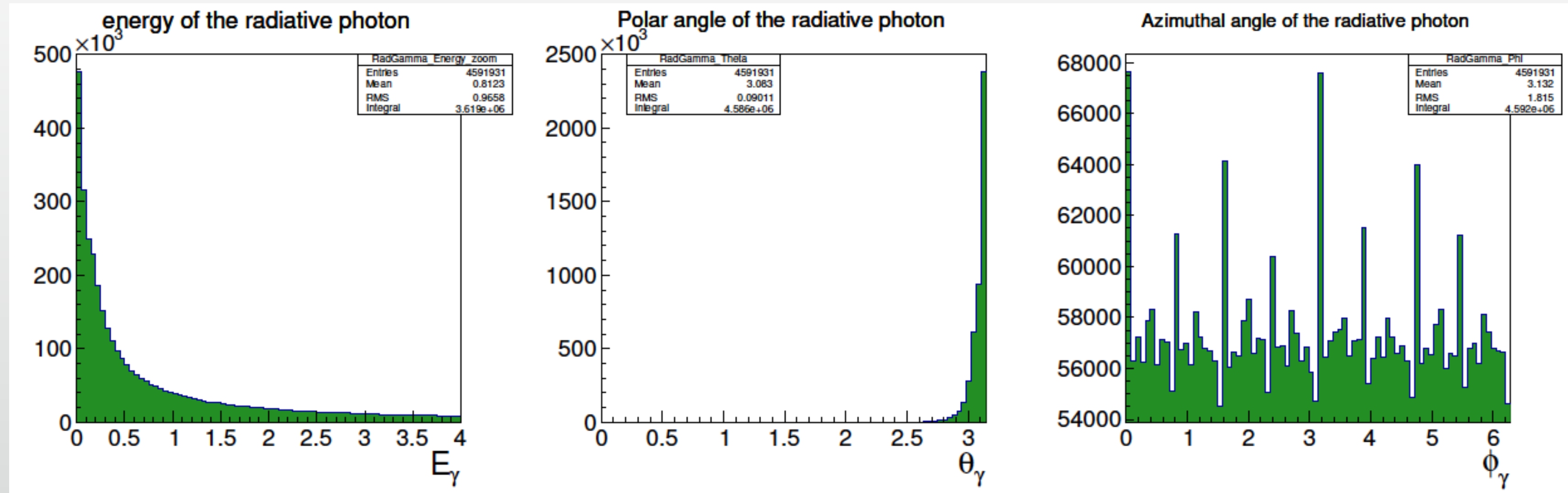


BACKUP:

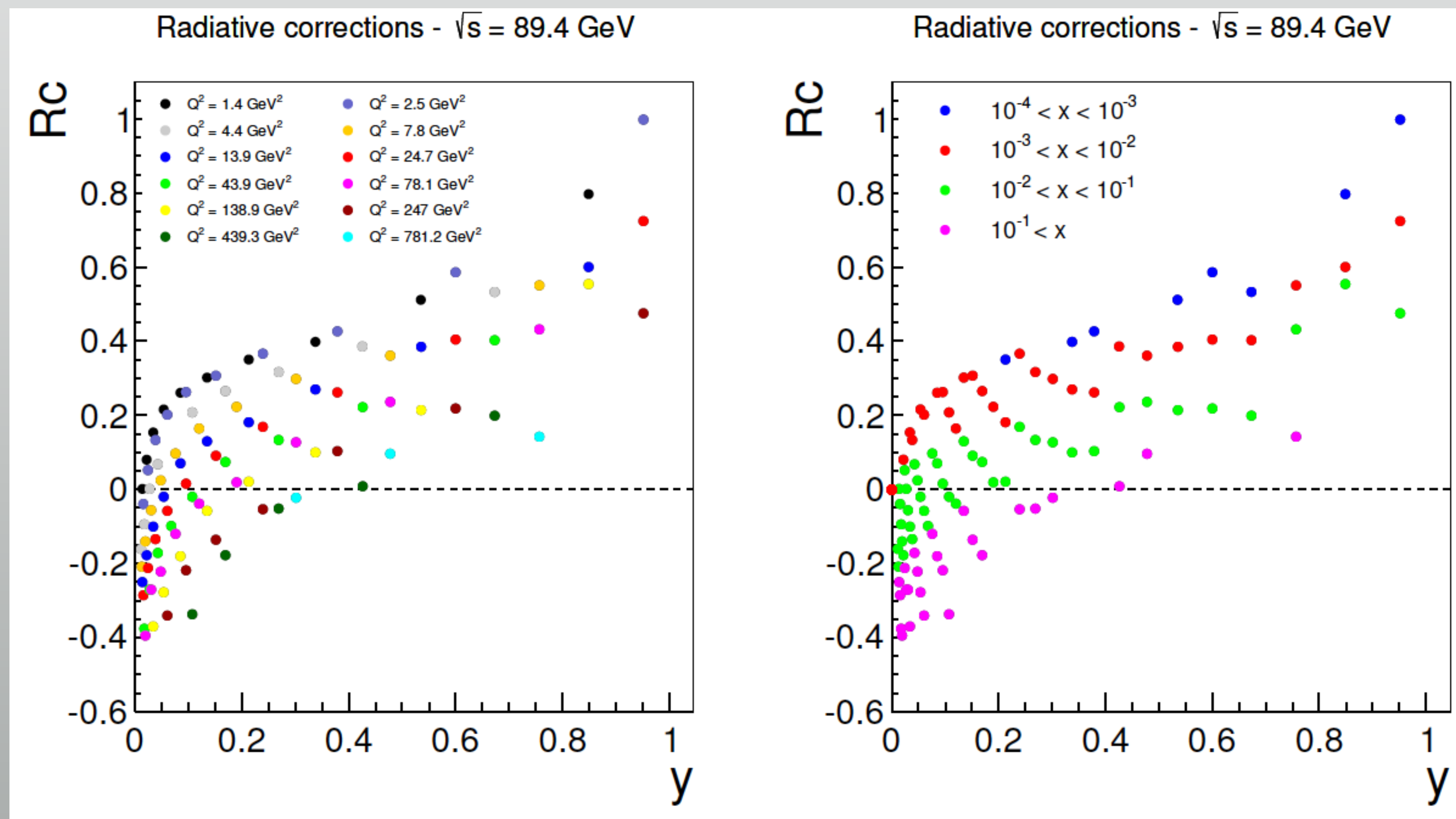
Radiative corrections @ EIC:

$$R_C = \frac{\sigma_{red}(O(\alpha))}{\sigma_{red}(born)} - 1$$

DJANGO



Preliminary!



LHeC pseudodata:

e(60)+p(7000)/Pb(2750)

Simulation

$\int\mathcal{L}$=10 fb^{-1} (ep)

$\int\mathcal{L}$=1 fb^{-1}/nucleon (ePb)

source of uncertainty	error on the source or cross section
scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale $\Delta E_h/E_h$	0.5 %
calorimeter noise (only $y < 0.01$)	1-3 %
radiative corrections	0.5%
photoproduction background (only $y > 0.5$)	1 %
global efficiency error	0.7 %

Full simulation of NC and CC with correlated systematic errors and optimum kinematic reconstruction method (electron at large y and 'mixed' at low y).
Numerical program, gauged/compared to H1 Monte Carlo simulation.
→ **All results have statistical and systematic uncertainty (corr+unc)**
The so-called model uncertainties at the LHeC will be much reduced as it provides precision data (CC for flavours, mc to 3 MeV, extended range, high x with high statistics etc.)
RC in eA is large source of uncertainty, needs photon tagger, still E-pz : 2%
For the simulation of the s,c,b data, background and tag efficiencies are considered

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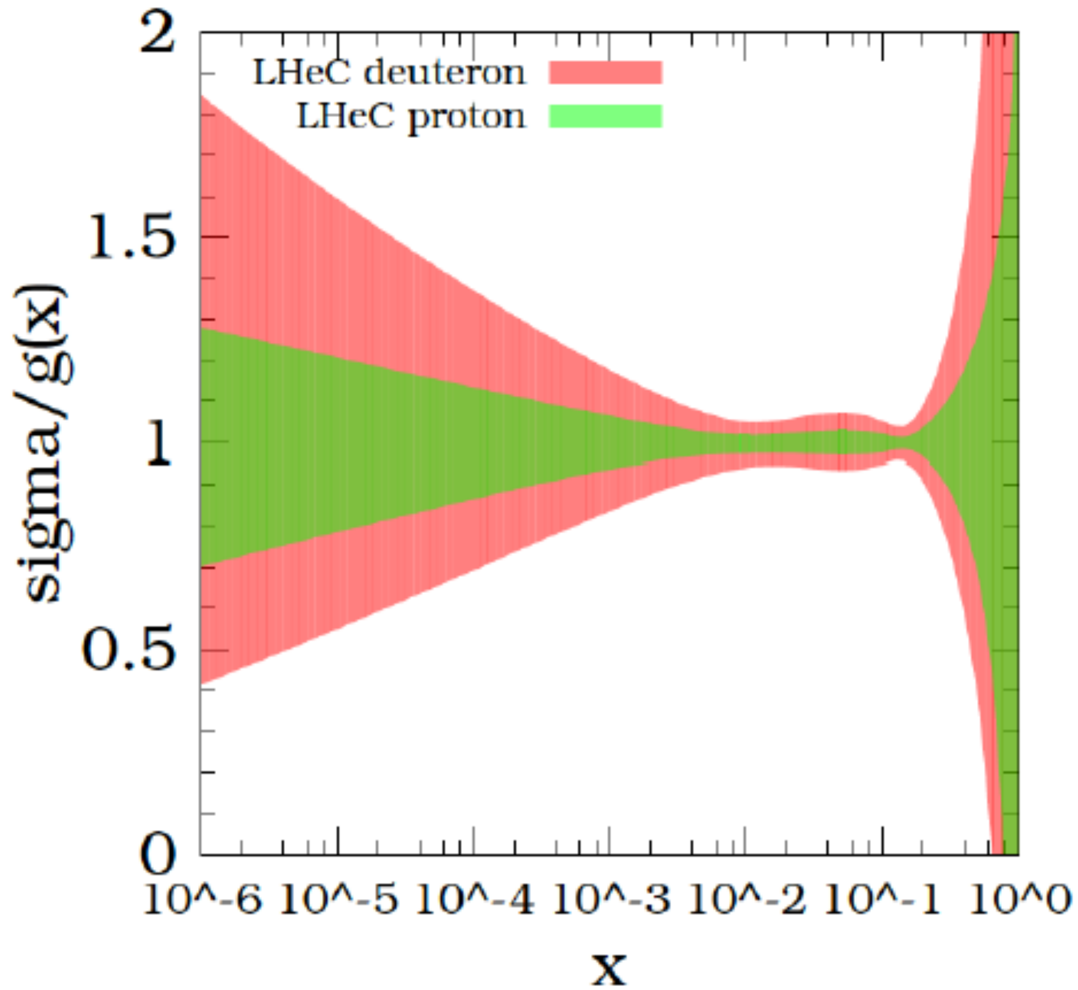
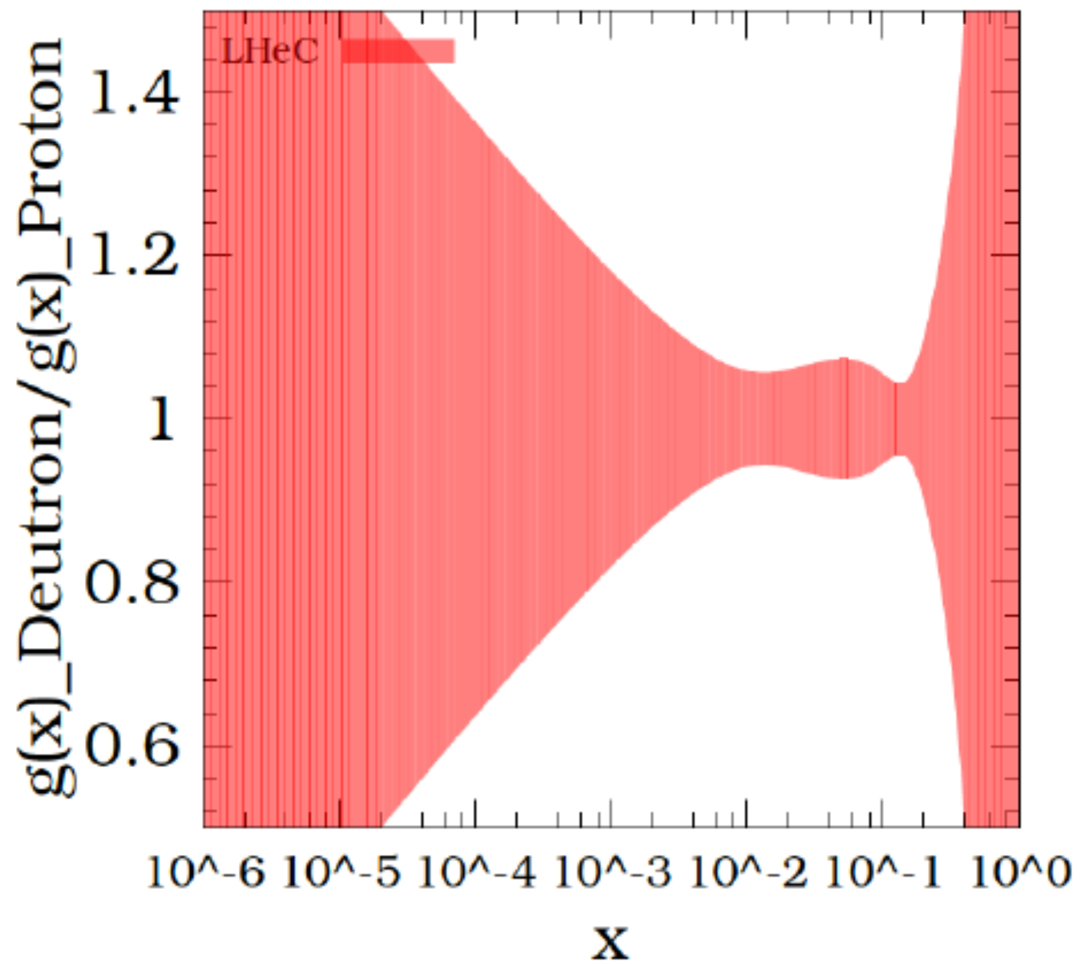
LHeC eA standalone fit:

Parton dependent nuclear effects

gluon

preliminary





Measure gluon in proton and nucleus (here used deuteron simulation).

Ratio should provide nuclear correction and its uncertainty, for each parton fitted

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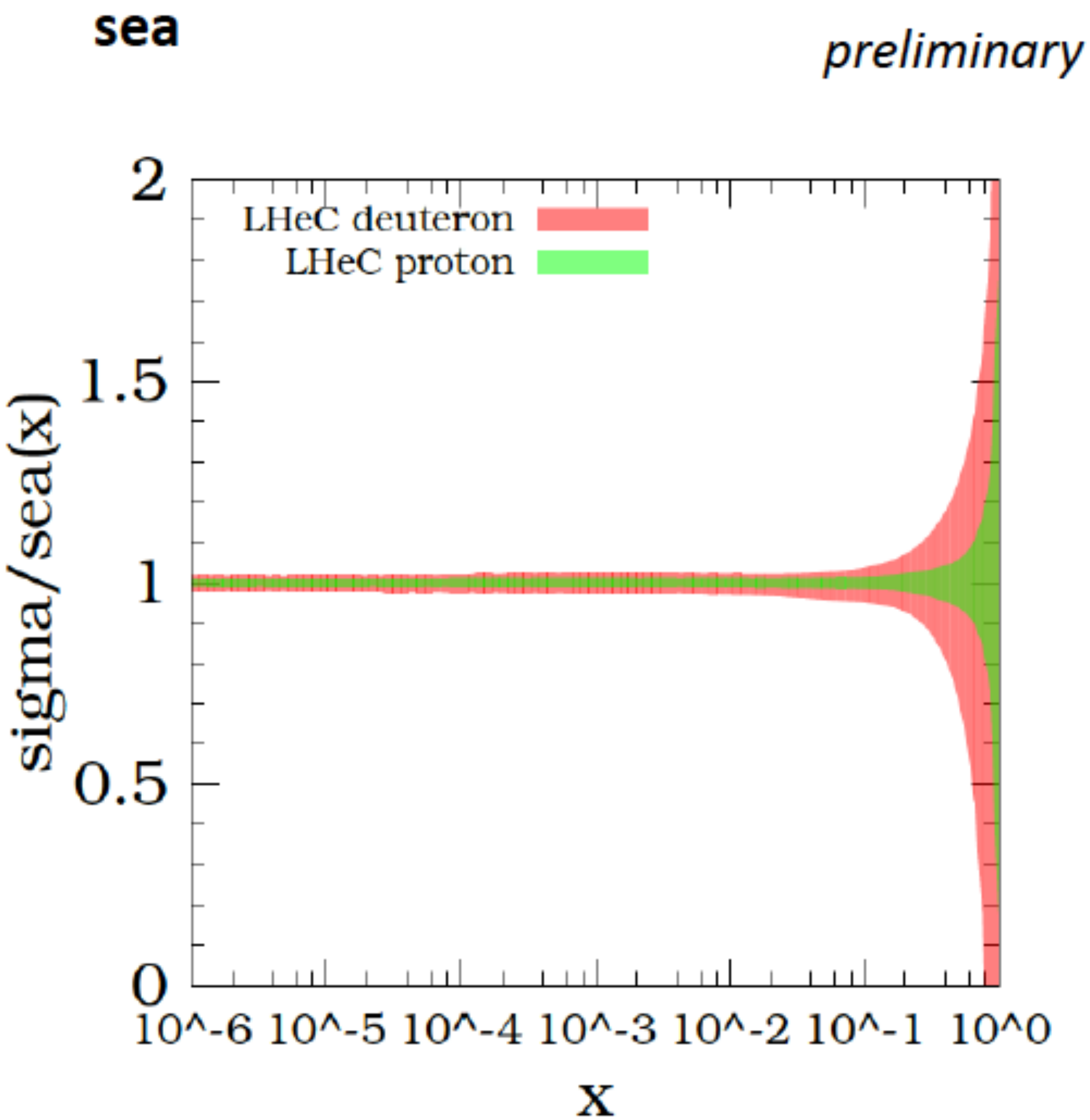

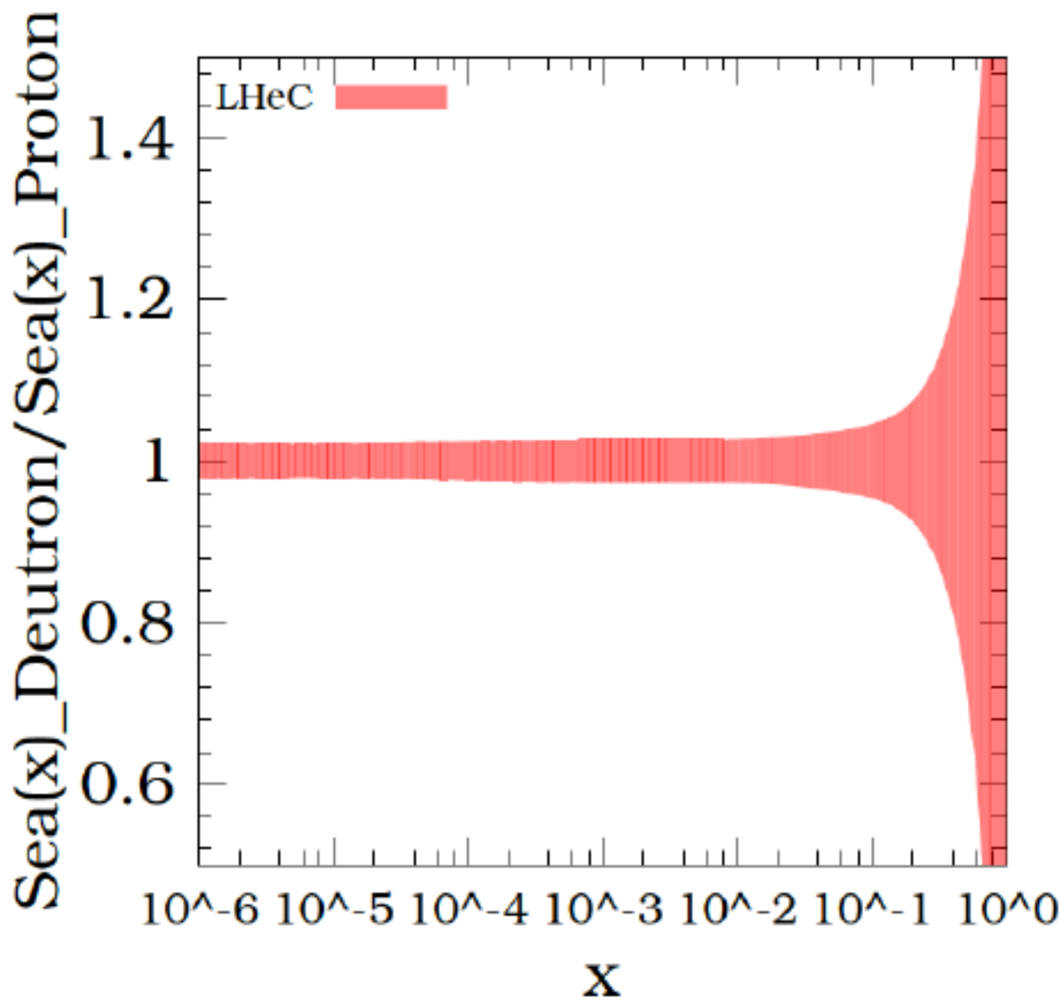

Measure sea in proton and nucleus (here used deuteron simulation).

Ratio should provide nuclear correction and its uncertainty, for each parton fitted

In progress valence and sea quarks..

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